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Variability management in safety-critical systems design & dependability analysis[†]

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Summary

Safety-critical systems are of paramount importance for many application domains where safety properties are a key driver to engineer critical aspects and avoid system failures. However, the integration of safety analyses in the development process is non-trivial. Also, the different usage contexts of safety-critical systems complicates component fault modeling tasks and the identification of potential hazards. In this light, better methods become necessary to estimate the impact of dependability properties during Hazard Analysis and Risk Assessment (HARA). Existing methods incorporating the analysis of safety properties in software product lines (SPL) are limited as they do not include hazard analysis and component fault modeling. The approach detailed in this paper presents an extension of previous work with conventional SPL approaches to incorporate safety analysis and requirements in the development of safety-critical systems. We also outline a case study belonging to the aerospace domain to illustrate how to model and reuse safety properties.

KEYWORDS:
Safety-critical systems, dependability analysis, safety, reuse, software product lines.

1 | INTRODUCTION

Systems are safety-critical where the occurrence of failures may have catastrophic consequences, e.g., damages to property, environment, injuries or loss of life. Commonly, the design choices made in different contexts can impact on quality properties, such as reliability, availability, safety, or security[1]. Thus, it is important that dependability[1] analysis be performed to identify potential threats that may lead the system to unsafe states. Safety-critical systems can be found in many complex domains with existing standards/considerations that provide guidance and compliance requirements that must be met for their development, e.g., ISO 26262[2] for automotive, DO-178C[3] and SAE ARP 4754A[4] for the aerospace domain. As part of this, safety guidelines establish that dependability properties of critical systems must be analyzed at different levels of abstraction, e.g., from requirements to component levels, before their release for operation.

One of the ways for building such systems is to adopt a Software Product Line (SPL) approach that integrates dependability engineering activities[5,6] in the development process. Existing compositional techniques[7,8,9] provide automated support for dependability engineering processes with seamless integration between system design and dependability analysis. Such integration contributes to a reduction in the complexity of dependability engineering activities and facilitates large-scale reuse, as illustrated in industrial examples from automotive[10,11] and aerospace domains[5,12]. However, even when adopting SPL strategies, the reuse of dependability information can still be challenging. Existing approaches only support the reuse of fault trees and FMEA (Failure Modes and Effects Analysis)[11,13,14,15,16] as key artefacts to identify how system failures are propagated in the design of the system. Fault trees and FMEA[17] artefacts can be automatically generated from the reusable dependability information. Thus,

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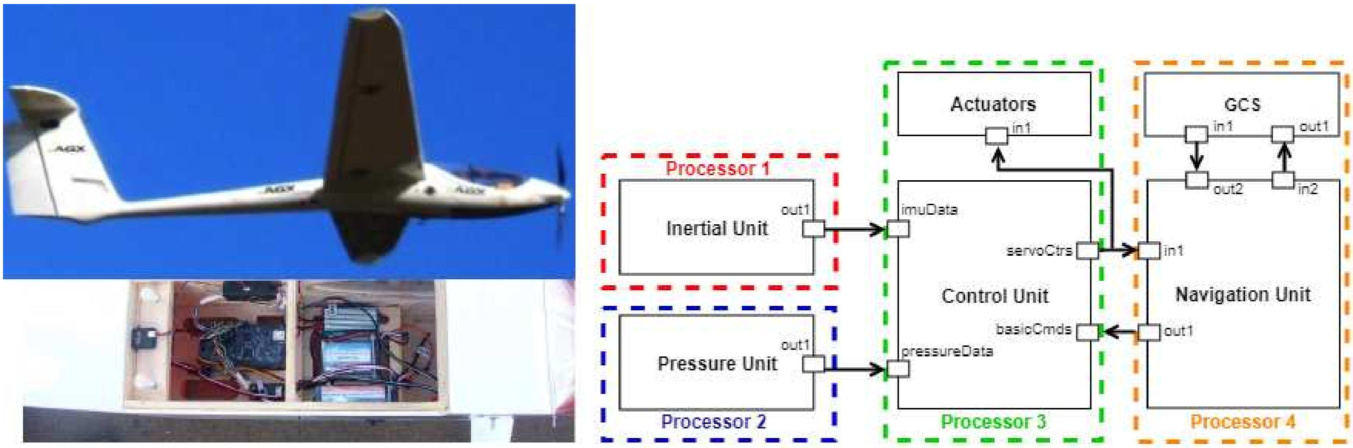
the effort, and costs of performing dependability analysis for specific system configurations/variants can be reduced, since such analysis is not performed from scratch.

One of the main benefits of reusing dependability information is improving the verification of dependability properties in different usage contexts. This paper presents an approach to facilitate the reuse of dependability information to handle unpredictable hazards[1] and component failures more efficiently, and ensure dependability properties. This research extends conventional SPL approaches [18,19,20], to include dependability information, focusing on the analysis of safety[2] and reliability[3] properties and its impact on traditional software product line life-cycle. The analysis of other dependability properties, e.g., *security* and *availability*, is outside the scope of this research. The major improvements on our previous work [22] consists of a detailed description of our approach and Tiriba case study, and a deeper analysis of the impact of design and usage context variations on system architecture and behaviour, allocation and decomposition of safety requirements[4], component fault modeling and propagation, and FMEA results.

The remainder of this paper is organized as follows. Section 2 presents the background knowledge of the Tiriba [24] unmanned aircraft system, used in the case study, and the research challenges. Section 3 presents our approach consisting of an extension of SPL activities to support dependability analysis for safety-critical systems. We illustrate in Section 4 a case study from the aerospace domain using the Tiriba Flight Control product line in different usage contexts. In Section 5, we present a discussion and an analysis of the impact of system and usage context feature variation on system design and dependability analysis. In Section 6, we describe the related work, and in Section 7 we present the conclusions and future work.

2 | BACKGROUND AND CHALLENGES

This section presents a general overview of the Tiriba unmanned aircraft system [25] to provide some context for the case study and the approach of this research. Tiriba is a small low cost autonomous electrical airplane developed by AGX Company, that is used for performing predefined missions and targeted applications. Such applications include agriculture (e.g., detection of crop diseases), environment monitoring, traffic monitoring, topographical surveys, inspection of transmission lines, and defence (Figure 1 (left)). The Tiriba unmanned aircraft system, shown in Figure 1 (right), mainly comprises four subsystems: inertial, pressure, control, and navigation units. Each subsystem is allocated to a dedicated microprocessor, in this case, PIC32 80 MHz micro-controllers.



(left) (right)

FIGURE 1 An overview of Tiriba unmanned aircraft (left) and system architecture (right) [25].

The inertial unit is responsible for estimating, at runtime, the current UAV (Unmanned Aircraft Vehicle) position by receiving information from inertial sensors and Global Navigation Satellite System (GNSS). The pressure subsystem aims at providing the UAV altitude, vertical airspeed, and

[1] Potential source of harm caused by the malfunctioning behavior of a system or a set of systems that implement a function [2].
[2] Freedom from unacceptable risk posed by hazardous failures [21].
[3] The probability that a component will perform its intended function satisfactorily for a prescribed time and under stipulated environmental conditions [21].
[4] The required risk reduction measure(s) associated with a given system hazard, or component failure [23].

aero-dynamical speed based on air pressure. The navigation unit is intended to guide the UAV along a route, to follow rules defined by the mission planner, and accomplish the tasks associated with each waypoint, e.g., taking pictures from a specific location. The Tiriba control unit or flight control, which is used in the case study, provides the following functions: *(i)* flight control mode, *(ii)* flight and setup commands, and *(iii)* checking flight conditions that are sent by the navigation system. Finally, the ground control station (GCS) sends and receives mission data to/from the UAV.

The Tiriba UAV was originally developed as a single system [25], but it has evolved into a SPL [24] to address the subsequent demand for newer, slightly different, versions. The first versions of Tiriba were developed targeting missions over private farms in Brazil. The Tiriba SPL [24] comprises 104 features grouped into *usage context*, *quality attributes*, *capability* (or *system/product* feature), *operating environment*, *domain technology*, and *implementation technique* feature categories defined in Lee and Kang's modeling approach [26]. Dependencies can be specified among these features using mapping tables showing inclusion *(v)*, exclusion *(x)*, and selection *(o)* relationships between features. For example, the mission abortion feature should be included when Tiriba UAV is flying in a controlled/segregated [27] airspace [24]. Relationships between system and usage context features can also be specified in separated feature models [28,29,30]. This paper focuses on the analysis of dependability properties, in terms of *safety* and *reliability*, of the Tiriba Flight Control System SPL (i.e., the control unit shown in Figure 1 (right)), detailed in Section 4.

Nowadays, one of the main problems in safety-critical systems is enabling the systematic reuse of the dependability assets, and verifying dependability properties at different levels of abstraction (e.g. requirements, architectural, and component levels) in a range of different configurations and usage contexts. This is important for identifying potential *hazardous behaviours* and their *causes*, *mitigating* the effects of *safety threats*, and understanding how *hazards* can be *propagated* in the *architecture* and *components* of safety-critical systems. As systems like Tiriba can operate in a range of different contexts and under different circumstances, it is important to support dependability analysis in different scenarios. More specifically, we focus on the following challenges: (i) ***Ch1****: enabling the systematic reuse of dependability information*, and (ii) ***Ch2****: ensuring safety and reliability properties of critical systems, e.g., pilot modes, in a range of unexpected situations.*

3 | DEPENDABLE-SPLE APPROACH

In this section we describe the DEPendable-SPLE approach as an extension of our previous work [22]. Firstly, we describe the impact of dependability in SPLs and outline how conventional software product line processes can be extended to support dependability engineering activities. Secondly we describe how to model the variability of safety information across different products of the modified SPL life-cycle.

3.1 | Dependability Engineering in Software Product Lines

Software Product Line Engineering (SPLE) and component-based approaches provide the benefits of large-scale reuse, contributing to reducing the time-to-market and costs, and increasing the quality of components. For these benefits, SPLE approaches have been largely adopted by industry in the development of critical systems, especially in automotive [10,11] and aerospace [12,5] domains. In the same way as critical systems built upon conventional approaches, critical systems built upon an SPL approach have to consider guidance defined in safety standards/considerations, e.g., automotive ISO 26262, and aerospace DO-178C and SAE ARP 4754A. Standards establish that dependability properties of a critical system should be analyzed at different levels of abstraction before its release for operation. At the requirements level, during hazard analysis, the potential threats and the risk that they pose to overall system safety are identified and determined. At the design level, the propagation of system failures throughout architectural subsystems should be analyzed, during component fault modeling, using failure logic analysis and/or Fault Tree Analysis (FTA) [17] techniques. Finally, at the component level, it is necessary to identify how components can contribute, directly or indirectly, to the occurrence of system failures (named hazards) using FMEA or Failure Modes and Effects Criticality Analysis (FMECA) techniques.

In a safety-critical SPLE process, variation in the system design and usage context[5] may impact on dependability properties. Thus, different *hazards*, with different *causes* and *risks* that they pose to the overall safety can be raised according to *design choices* and targeted *contexts*. Additionally, *safety requirements*, in the form of *system functions* and/or Safety *Integrity Levels*[6] (SILs) with different degrees of stringency should be allocated so the effects of *system* or *component-level* failures can be *mitigated* according to the targeted design and usage context.

Since system dependability properties may change from one targeted product configuration/variant and context to another, dependability analysis for *re-configurable* systems or systems built upon an *SPLE* approach should be performed with awareness of variation in the design and usage context. This is needed to *ensure* the safe use of *reusable* architectural subsystems and components in a range of targeted product configurations and contexts. Thus, we should manage variability in dependability assets from the early stages of a safety-critical SPLE processes. A way to do that is to add mappings to the *application variability model* that link *context* and *design* variants, specified in the domain variability model, to their realization in the dependability assets (e.g., hazard analysis and component fault models) [31].

[5] Usage context relates to where and how a system, a system function, a system configuration is used [26].

[6] It specifies the *reliability*, e.g., in terms of *likelihood* and *severity*, associated with a given system or component-level failure, or system function.

Existing variant management techniques[11,32,33,34,35,36] provide support for managing variability of requirements, architecture, components, source code and test case assets. However, these techniques were not originally designed or used for supporting variability management in system models enhanced with dependability information, such as those specified with the support of compositional modeling techniques like OSATE AADL[7], HiP-HOPS[8], or CHESS[9].

The management of variability in the dependability information enables automated/semi-automated ***traceability*** of variation in the design and usage context throughout the dependability assets. This leads to the systematic reuse of both design (architecture and behaviour) and dependability information. The *systematic reuse* of *dependability* assets may contribute to *reducing* the *complexity*, *effort*, and *costs* of performing safety analysis for specific *system variants*, or *versions* of a particular variant, since such analysis does not need to be performed from scratch. Therefore, we can automatically generate, with the support of compositional techniques[7,8,9], fault trees and FMEA dependability artefacts for a specific system variant from the reusable dependability information. FTAs and FMEA assets are required by cross-domain safety standards, regulations, and considerations, e.g., aerospace SAE ARP 4754A, as evidence for *certification* of critical systems and the *safety approval* of their components.

It is only possible to consider dependability analysis artefacts as part of the SPL core assets if the application variability model[31] contains information about variation points/variants and their realization into the dependability model (these can be in the form of annotations in the system model). Thus, the dependability model should be included in the SPL core assets to enable the systematic reuse of dependability information together with other SPL assets (e.g., requirements and design).

The management of variability in dependability models can contribute to *reducing* the *costs* of generating *safety* assets for a larger number of system variants built upon the *SPL core assets*. Although existing variant management techniques, e.g., Base Variability Resolution (BVR)[36], were not designed to support variability in the dependability model, they can be adapted to enable support for variability management and derivation of product-specific system models enhanced with dependability information.

3.2 | Adapting Conventional SPL Approaches to support Dependability Engineering

Software Product Line Engineering for critical systems is distinguished from conventional SPL approaches[31,18,19,20] as they consider the impact of *design choices* and *usage context*[26] on system **dependability** properties throughout the SPL life-cycle (see Figure 2), in compliance with safety standards/considerations[2,3,4]. In Figure 2, related conventional SPLE and dependability engineering activities are grouped into labeled boxes. Modified SPLE sub-sub-phases are highlighted, and dependability activities added to conventional product line processes are filled with gray. Dotted activities represent issues outside the scope of this paper. In the *problem space* domain definition, i.e., during SPL requirements engineering, *dependable/safety-related* features and their relationships with *system/design* features should be identified and specified, together with design and usage context features. This results in the product line feature model, as highlighted in Figure 2 (i).

From the perspective of safety-critical SPLs, *interactions* among different types of features (e.g. *dependable-related*, *system/design*, and *usage context*) can be used to establish safety certification criteria that might impact on SPL *architectural/design decisions* aiming at achieving a target *safety level*, and *dependability properties*. After specifying a preliminary SPL design, we can perform an analysis of *interactions* between *dependable*, *system*, and *context* features to derive candidate scenarios (see Figure 2 (i)) to guide engineers during *hazard analysis* for identifying potential threats (hazards) and estimating their risk for the overall safety across a set of system variants. In addition to conventional SPLE processes, we should include *Hazard Analysis and Risk Assessment* (HARA), along with *allocation/identification of safety requirements*, dependability engineering activities between *SPL requirements* and *initial stages* from the design in the domain engineering phase (see Figure 2 (ii)).

In the SPL architecture and implementation, i.e., in the *solution space*, we should specify the realization of *dependable-related* system features, e.g., *redundancy*, and their *relationships* with other features in the product line architectural and/or behavioural models, and *component* implementations. Later, dependable-related architecture and component assets should be added to the SPL core assets. Additionally, we should incorporate *component fault modeling* dependability engineering activity into the SPL architecture *sub-phase* (see Figure 2 (ii)).

During *component fault modeling*, engineers identify how *components* can contribute to the occurrence of *hazards* in each scenario under analysis, thus, generating a set of varying *component fault models*. We can perform both *hazard analysis* and *component fault modeling* in parallel to the SPL design and component implementation with the support of compositional techniques[7,8,9]. It is important to highlight that domain-specific hazard analyses and component fault models are part of full-up safety considerations, i.e., safety/dependability assumptions valid for a set of targeted system variants (scenarios).

Still in the *domain engineering* phase, in order to achieve the systematic reuse of SPL core assets, conventional SPL processes demand the specification of mappings linking system design features to their realization in the SPL architecture along with components in the variability model, during integration of variability information shown in Figure 2 (ii). A variability model or application variability model establishes traceability links between *application requirements*, specified in the *feature model*, and *domain artefacts* such as *architectural components* and *test cases*[31]. Moreover, safety-critical SPL processes also demand the specification of mappings in the SPL variability model that link *dependable-related* features to their

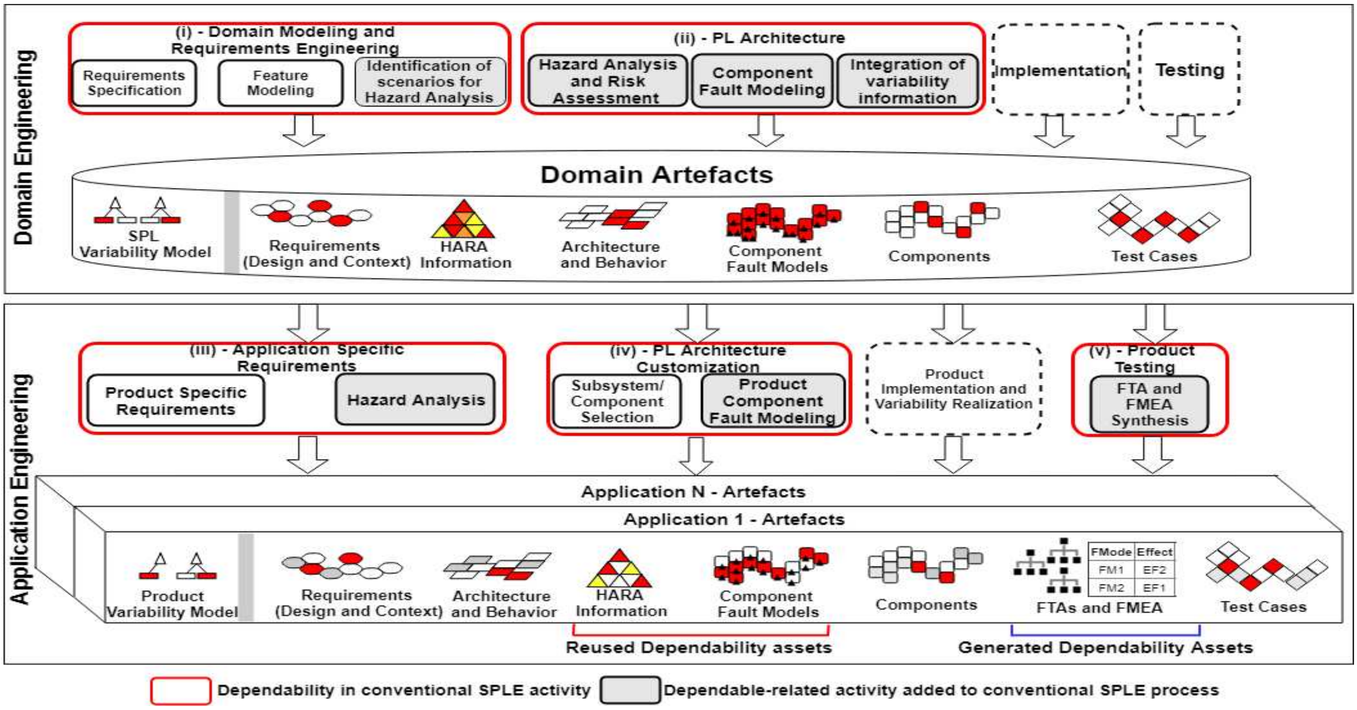

Domain Engineering
(i) - Domain Modeling and Requirements Engineering
Requirements Specification
Feature Modeling
Identification of scenarios for Hazard Analysis
(ii) - PL Architecture
Hazard Analysis and Risk Assessment
Component Fault Modeling
Integration of variability information
Implementation
Testing
Domain Artefacts
SPL Variability Model
Requirements (Design and Context)
HARA Information
Architecture and Behavior
Component Fault Models
Components
Test Cases
Application Engineering
(iii) - Application Specific Requirements
Product Specific Requirements
Hazard Analysis
(iv) - PL Architecture Customization
Subsystem/ Component Selection
Product Component Fault Modeling
Product Implementation and Variability Realization
(v) - Product Testing
FTA and FMEA Synthesis
Application N - Artefacts
Application 1 - Artefacts
Product Variability Model
Requirements (Design and Context)
Architecture and Behavior
HARA Information
Component Fault Models
Components
FMode
Effect
FM1
EF2
FM2
EF1
FTAs and FMEA
Test Cases
Reused Dependability assets
Generated Dependability Assets
Dependability in conventional SPLE activity
Dependable-related activity added to conventional SPLE process

FIGURE 2 Conventional software product line processes enhanced with safety/dependability engineering activities.

realization in the dependability model (i.e., HARA information and component fault models). This is necessary to enable support for the systematic reuse of dependability information in the application engineering phase.

Dependable-related features also impact on the development of test cases for testing dependable SPL components. Thus, in the safety-critical SPLE, we should add dependability engineering activities to the domain engineering phase. Variability management and other traditional SPLE activities, e.g., domain modeling, should be extended for considering the impact of SPL variation on system safety/dependability properties.

In the safety-critical SPL application engineering phase, we need to extend *product specific requirements*, i.e., product feature modeling in the problem space, by considering the *specification* and *selection* of dependable-related features, which impact on both design and dependability assets, together with the specification and selection of system and usage context features. Still in the application engineering phase, we need to modify the variability resolution process of a safety-critical SPL by considering mappings linking dependable-related features to their realization in both SPL design and dependability assets defined in the variability model. This is required to enable the generation/derivation of both design, HARA information, and component fault model safety assets, i.e., *solution space*, for a specific system variant according to the *feature selection*. The goal is to achieve the systematic reuse of both HARA information and component fault models, reducing potential effort and costs for achieving product certification[7] and component approval in compliance with domain-specific safety standards [2,4] and/or considerations [3].

Finally, we should add the same dependability engineering activities from the domain engineering phase, e.g., hazard analysis and component fault modeling, together with *Fault Tree Analysis and FMEA Synthesis*, to the application engineering phase (see Figure 2 (iii), (iv) and (v)). This is necessary to enable support for the analysis of dependability properties of a specific system variant obtained after product derivation (i.e., PL Architecture Customization).

3.3 | DEPendable-SPLE: an overview

Here we present the DEPendable-SPLE approach, which extends traditional SPLE methods [18,19,20,31] with the provision of support for safety/dependability engineering, and variability management in dependability assets (dependability model).

The DEPendable-SPLE approach activities and their associated work products, in both domain and application engineering phases, are illustrated in Figure 2. In this paper we focus on dependability engineering for safety-critical SPL architectures, so modifications in traditional SPLE

[7] It means compliance to regulations in avionics, since there is no safety certification in aviation.

activities such as domain and application requirements engineering, design, and testing are not detailed. Instead, we have added four dependability engineering activities to the domain engineering phase, and we have extended traditional SPLE variability management to enable support for the management and resolution of variability in the dependability model. In the application engineering phase, the product derivation process (i.e., PL architecture customization) was extended to allow the resolution of variability on the SPL dependability model. This supports the generation of variant-specific design and dependability assets according to chosen features defined in the application feature model. Although existing variant management techniques [11,32,33,34,35,36] were not originally designed to support variability in a system model enhanced with dependability information, we have developed an adapter to the BVR toolset [36] to enable support for managing variability in AADL system models enhanced with AADL error annex dependability annotations. This adapter allows BVR to communicate with OSATE model editors. The detail about the AADL-BVR adapter is outside the scope of this paper.

The DEPendable-SPLE approach is structured to comply with safety assessment processes established in cross-domain standards/considerations [2,3,4]. Enhancing SPLE processes with safety engineering life-cycle activities may contribute to reducing the effort and costs of achieving *certification* of critical *systems* along with *component approval* in compliance with standards/considerations, e.g., ISO 26262 Parts 3 and 4 for automotive, and SAE ARP 4754A safety process for avionics. In our approach, SAE ARP 4754A safety processes or ISO 26262 Parts 3 and 4 activities, i.e., *PL Architecture* box in Figure 2 (ii), are conducted after *feature modeling* and *identification of scenarios for hazard analysis* (*Domain Modeling and Requirements Engineering* box in Figure 2 (i)). It is important to highlight that there is a two-way process between the ***standards*** and ***domain analysis***: the choice of the *standards* constrains the *domain model* and vice-versa. State of the art model-based and compositional dependability analysis techniques [7,8,9] can be used to support engineers performing dependability activities through the SPL life-cycle. The DEPendable-SPLE approach is applicable independently from the underlying variant management and compositional safety/dependability analysis techniques. Each of the activities is described in the following sections.

3.4 | DEPendable-SPLE: Domain Engineering Phase

In the first step of the domain engineering phase, dependability analysis scenarios are defined from the analysis of interactions among *product/system* and *usage context* features specified in the SPL domain model. After scoping SPL dependability analysis to a set of targeted scenarios, dependable-related steps such as hazard analysis, along with the allocation of safety requirements, and component fault modeling, are iteratively and incrementally performed for each scenario. Finally, features are linked to their realization in architectural and behavioral models, plus their dependability artefacts as part of safety-critical SPL variability modeling. Each domain engineering approach step is detailed in terms of its inputs, purpose, and outputs.

3.4.1 | Domain Modeling and Requirements Engineering

In this sub-phase, we describe the elicitation of safety/dependability requirements, how we can model the variability of these requirements and other system features, and how we perform the identification of scenarios for hazard analysis. The *elicitation of safety/dependability requirements* is not the main goal of our approach. The purpose of this sub-phase is to analyze different system configurations belonging to the target safety-critical system's domain, e.g., avionics, to identify common requirements. However, it is not possible to guarantee that these common requirements belong to safety aspects of the system before performing *hazard analysis*. After this activity, we perform the *feature modeling* task.

Feature Modeling:

In feature modeling, we specify *system* and *usage context* commonality and variability in both SPL feature and context models. System variability can happen in: *capability*, *operating environment*, *domain technology*, *implementation techniques*, or *quality attribute* features [18,26]. *Capability* comprises features regarding end-user visible characteristics. *Operating environment* comprises features associated with the target environment where a given software product is operated. *Domain technology* relates to features representing specific domain techniques or tools that can be used to implement the SPL core assets. *Implementation techniques* are features regarding specific implementation strategies, e.g., *redundant* or *non-redundant* control system architecture features in the avionics domain. *Quality attributes* refer to features that the SPL products must address such as *usability*, *maintainability*, and *data integrity checking*. *Usage context* features relate to *where* and *how* the software product line is used [26].

Features can have relationships with each other. These relationships can be of the following types [26]: *requires* (R), *excludes* (E), *works for* (WF) or *work against* (WA), which can be classified as *n-to-m*. Thus, a particular feature can *require*, *exclude*, *work for* or *against* one or more other *features*. There are even cases where two or more features may require, exclude, or are working for/against a single feature. We have considered this feature classification for this paper. Combinations among *system* and *usage context* features act as a key driver during software product line design for safety-critical systems, with dependability analysis and modeling, and product derivation (instantiation). Such multi-perspective features and combinations have a direct influence on SPL *design decisions* and *dependability analysis* when aimed at achieving approval and compliance with safety standards/considerations.

The SPL *system feature model* comprises features visible to the end user, e.g., *capability*, *operating environment*, *domain technology*, *implementation technique*, and *quality attribute* features. The *context model* comprises features describing variation on the SPL *environment*, i.e., where and how system features are intended to be used. The strategy of separating SPL domain modeling into two interconnected feature models is based on the Hartman and Trew[28] feature modeling approach and its refinements[29,30]. Such approaches allow a clear specification of interactions, e.g., *requires* and *excludes*, among *system* and *usage context* features that may impact on both *design* and *dependability* assets. The outputs of this activity are the SPL *feature* and *usage context* models and their *connections*. For example, we can have an SPL system/product feature model (***FM***) with *F1* mandatory and *F2* optional *system* features, and a context model (***CM***) with *CX1* and *CX2* mutually exclusive *usage context* features, and a relation ***includes*** implying that the *choice* of the *CX2* context feature triggers the *selection* of the *F2* system feature.

Usage context features in *isolation* or when *combined* with *system* features can impact on the product line *design* and *dependability analysis* in the domain engineering phase. Thus, variation in the selection of system and usage context features may lead to different design choices, resulting in different *system* and *component* level *failures* during SPL dependability analysis. We can use combinations among *system* and *usage context features* to propagate/specify variation in *safety information* in the *feature model*. A detailed description of an approach to support the specification of safety-related features and their interactions on feature modeling is outside the scope of this paper.

Identification of Scenarios for Product Line Hazard Analysis:

The last step of the domain modeling sub-phase is the *identification of scenarios for hazard analysis*. The ***inputs*** for this activity are: the *SPL feature and context models*, containing the specification of *system* and *usage context* features and their *interactions*; a preliminary SPL *design*, produced during earlier stages of SPL architecture sub-phase (see Figure 2 (ii)); and analysts' *domain knowledge*. The ***purpose*** of this activity is identifying, from the analysis of *interactions* among *system/product* and *usage context* features, a set of system variants (*scenarios*) relevant for the stakeholders by combining system and usage context features. These scenarios can be further considered to guide engineers during SPL dependability analysis.

The identification of scenarios encompasses the following *tasks*: ***(i)*** identifying combinations among system/product features, which represent system functions, and their relationships with elements from architectural and behavioural models, to derive system/product variants; ***(ii)*** for each identified system variant, we analyze combinations among features to establish potential *usage contexts* in which the given system variant can operate; and finally, ***(iii)*** we derive different *scenarios* by combining the identified *system* and *usage context* variants. However, since it would be prohibitive to perform such analyses covering all system/usage context variants, we can use the analysts' domain knowledge, and relevant product variants for the stakeholders as criteria to assess candidate scenarios to be considered when performing SPL dependability analysis[6,24,37].

The ***outputs*** of this activity are combinations of system and usage context variants, i.e., *scenarios*, relevant for the stakeholders. Thus, considering the SPL feature model (**FM**) with *F1* mandatory and *F2* optional system features, and a context model (**CM**) with *CX1* and *CX2* mutually exclusive features, and a relation *CX2* includes *F2*, we have the following scenarios: ***SC1*** = F1, CX1, and ***SC2*** = F1, CX2, F2. We can further consider these scenarios during SPL hazard analysis.

3.4.2 | Product Line Architecture

In the safety-critical SPL development process, *system* and *usage context* features, and their *interactions* define *constraints* that may impact on *design decisions* aimed at achieving *safety certification*. Thus, different design choices must be taken according to the selection of system and usage context features. In both non-critical and safety-critical software product lines, *variation points* and their *variants* defined in the SPL *feature* and *context* models have a direct impact on the derivation of product-specific architectural and behavioural models. In the development of critical systems, the *system architecture* is often expressed in *data-flow*[7,8] oriented models, and the system behaviour is often expressed in Finite State Machines (FSMs). So, in this sub-phase, variability in the SPL domain model propagates throughout the design.

Considering **FM** and **CX** product line feature and context models, and **SC1** and **SC2** scenarios, we can have a hypothetical aerospace SPL architectural model (**PLA**) comprising: *S1* and *S2* mandatory *subsystems*, and a *C1* optional *component*, where *S1* and *S2* subsystems represent the realization of the *F1* system feature and *CX1* context feature (SC1 scenario). On the other hand, *C1* component represents the realization of the *F2* system feature. We can also have **FSM1** state machine with a set of states (*ST*), i.e., *st1* and *st2* mandatory states, and *st3* optional state, and a set of transitions (*T*): *t1*, *t2*, and *t3* encapsulating common and variable behaviours. After that, still in the second sub-phase of domain engineering, we will use as input the *scenarios* relevant for the stakeholders together with the system architecture, composed by different subsystems and components, and we will identify potential failures both in subsystems and components that can be found in each scenario. Finally, we will integrate the variability information produced in the domain modeling with the SPL design and dependability model elements.

Hazard Analysis and Risk Assessment:

The ***inputs*** for this activity are a targeted *scenario*, i.e., product/usage context variant, relevant for the stakeholders, along with SPL *architectural* and *behavioural* models. After choosing a given scenario earlier identified in the previous step, HARA is carried out aimed at identifying combinations of contributing component failures/faults that may lead to the occurrence of system-level failures named hazards. We can specify *hazards* by means of logical expressions, such as **AND**, **OR**, and **NOT** operators, involving potential failures in SPL architectural subsystems/components that might lead to system failures. These failures are generally stated in terms of failure types that typically include: *omission*, *commission*, *value*, *early* or *late* failure modes. Firstly, we analyze interactions among *core* architectural components to identify potential *hazards* that can emerge from these *interactions*. Later, *optional*, *alternative*, and mutually *inclusive/exclusive* architectural components, representing *variability* defined in the targeted scenario, are analyzed to identify potential hazards that can emerge in such scenarios. This step results in a list of variant-specific hazards.

Considering a **PLA** hypothetical aerospace SPL architecture model comprising *S1* and *S2* mandatory *subsystems* and a *C1* optional component, an *omission* of *S1.out1* **AND** *omission* of *S2.out1* can cause the *Omission of commands* hazard in the **SC1** scenario. In the next step, still at the **system level**, we estimate and classify the risk posed by each identified hazard in each scenario using the probabilistic risk tolerability criteria defined in the targeted domain standards. DO-178C[3] and SAE ARP 4754A[4] aerospace safety considerations establish five software levels, DAL A to DAL E, and prescribe that risk assessment should be performed on the basis of severity and probability levels to classify a system hazard at a given software level. Aerospace MIL-STD-882E[38] standard practice for system safety provides a hazard/mishap risk matrix that relates range values for severity and probability attributes with software levels. Thus, engineers estimate the risk posed by a system hazard by assigning values to reliability attributes, e.g., severity and likelihood, and later on by checking the corresponding software level in the risk matrix during safety assessment. For example, if the *severity* of the occurrence of *Omission of commands* is *Catastrophic* with *probability of occurrence* of *10e-3 per hour of operation*, then, its risk level is **DAL A** according to DO-178C and MIL-STD-882E mishap risk matrix.

The **risk** assigned to a **hazard** at the system level is inherited by *software* that contributes to the occurrence of that hazard, to address the targeted software level, e.g., DO-178C DAL A. The assignment of *software levels* to components is modified via architecture. Architectural strategies may contribute to reducing the impact of failures. Thus, different *architectural choices* may change the assignment of software levels to components. Considering the *Omission of commands* hazard, the addition of *C1* optional component to the architecture may change the software levels assigned to *S1* and *S2* mandatory subsystems comply with DAL A. This is detailed in the allocation and decomposition of safety requirements, which is also part of the system safety assessment process. The ***outputs*** of this activity are: a *list of identified hazards and their risk classification* for each analyzed scenario.

Allocation and Decomposition of Safety Requirements:

This activity is part of product line *hazard analysis and risk assessment*. From the analysis of *product line hazards*, we specify *system* and *functional safety requirements*, and allocate *Safety Integrity Levels* (SILs) for *eliminating* or *minimizing hazard* and/or *component* failure *effects* on the overall safety. A *system safety requirement* is the risk reduction measure to mitigate hazard effects. A *functional safety requirement* relates to design and implementation decisions, stated in the form of system functions, intended for eliminating or minimizing the effects of failures on the overall system dependability. A SIL or *safety integrity requirement* represents the reliability, e.g., in terms of *probability* and *severity* attributes, associated with a given *component failure/fault*, *hazard*, or *functional safety requirement*. Reliability attributes may change from one domain-specific standard/consideration to another.

Cross-domain safety standards establish a set of levels of integrity, ranging from most stringent to least stringent, to classify the risk posed by safety threats to the overall system dependability based on the: *values* assigned to *reliability* attributes and their position in the standard risk matrix. SAE ARP 4754A and DO-178C aerospace safety considerations define five levels of integrity, named Development Assurance Levels (DALs). **DAL A** is the most stringent, and **DAL E** the least stringent. Thus, in aerospace safety considerations, we can classify the risk posed by a given *system hazard* or *component failure* as **DAL A**, **B**, **C**, **D**, or **E**, based on the range of the values assigned to *severity* and *probability* reliability attributes. The ISO 26262 automotive standard also establishes five levels of integrity, named Automotive Safety Integrity Levels (ASILs), ranging from **Quality Management** (QM), the least stringent one, to **ASIL D**, the most stringent, to classify the risk posed by system/component failures. In automotive ISO 26262, we assign an ASIL, to a hazard or a component failure, based on the values assigned to *severity*, *controllability*, and level of *exposure* attributes.

The allocation of SILs to mitigate the effects of hazards or component failures may impact on the *system development costs*, since *achieving a given SIL* demands addressing *objectives*, by performing *system engineering activities* for producing a set of *development artefacts* established in the targeted standard/consideration to achieve safety approval according to the *level of integrity*. The assignment of standard-related *objectives* to be addressed, activities to be performed, and artefacts to be produced to achieve a given level of integrity (certification level) may change from one domain-specific standard to another[39,40].

In this step, we specify *system* and *functional safety requirements*, and SILs that should be allocated to each identified *hazard* according to its risk classification. For example, when considering the values assigned to *severity* and *probability of occurrence* of *Omission of Commands* in the given **SC1** scenario, as part of the SAE ARP risk assessment process, we should assign **DAL A** to mitigate the effects of this hazard. On the other hand, the addition of the *C1* component to the product architecture in **SC2** increases the system reliability, assuming that this component demonstrably share, with other components, the responsibility of keeping the system operating in a healthy state. Thus, a less stringent **DAL B** is sufficient to mitigate the effects of *Omission of commands*. It is important to highlight that the addition of a component in the architecture does not necessarily increase the system reliability. This can happen only if the addition is in such a way to demonstrably share the responsibility with other components to addressing a given software level. However, to ensure the safe usage of SPL *subsystems* and *components*, which contribute to the occurrence of this hazard, across a set of system variants, we should still assign the more stringent DAL A. Moreover, it is possible to further decompose the SILs allocated to system *hazards* throughout contributing *components* and their associated *failure modes*.

Allocating *stringent* SILs to mitigate *hazard effects* may impact on the definition of stringent standard's *objectives*, and *development activities* for producing *expensive* artefacts to achieve safety approval. This can result in increasing both system development and production costs. *Higher SILs* generally means *higher costs*, as meeting most stringent *objectives* typically require more *safety measures*, and *development effort* to deliver higher-quality components. ***SIL decomposition*** allows a safety-critical system architecture to meet a particular ***SIL*** assigned to a ***system-level failure*** without all contributing ***software components*** having to meet that ***SIL***. For example, if a *system failure* is raised only when *two independent* components ***fail together***, these *components share* the responsibility of meeting the ***SIL*** allocated to mitigate the effects of the given *system failure*.

Prescriptive and process-oriented safety standards and regulations [2,4] establish ***rules*** for ***decomposing*** **SILs** allocated to *system failures* throughout contributing *component failures*. In SAE ARP 4754A, if we allocate **DAL A** to mitigate a *system failure*, e.g., *Omission of commands*, caused by failures in two independent components[8] (*S1* and *S2*), we can respectively allocate **DAL A** and **DAL B**, or **DAL B** and **DAL B** to *S1* and *S2* subsystems to address **DAL A**. This probably reduces development *effort* and *costs* for achieving safety approval in comparison with addressing **DAL A** requirements in both subsystems. SIL decomposition allows the efficient allocation of SILs so that we can achieve *safety approval* in *compliance* with standards *without* being *unnecessarily stringent* or *expensive* when addressing *objectives*. We can perform SIL decomposition with the support of automated design optimization algorithms [8,41], built upon genetic, penalty-based, and Tabu-Search meta-heuristics techniques, after identifying how *components* can *fail* and their contribution to the occurrence of *hazards* during component fault modeling. *Rules* for decomposing SILs may change from one domain-specific standard to another. Thus, design optimization algorithms available in the literature provide support for decomposing: aerospace DALs [41], built upon SAE ARP 4754A [4] DAL decomposition rules, and automotive ASILs [8] based on ISO 26262 [2] ASIL decomposition rules.

Variation in the **SILs** allocated to *system hazards* can be further propagated throughout the SILs allocated to mitigate the effects of component failures. Additionally, engineers can obtain product line SIL decomposition results, which provides the SILs that should be allocated to ensure the safe usage of SPL components across a range of system variants, from the automated analysis of multiple product-specific SIL decomposition results [6]. Performed early in the design, it can support engineers in the specification of a *cost-effective* SPL development process. The support for decomposing SILs in SPL architectures is outside the scope of this paper.

Component Fault Modeling:

The ***inputs*** for this activity are: an *SPL architecture model* and *HARA information*. From the analysis of the identified *hazards* that can be raised in a particular scenario, we can make *assumptions* about how architectural *components* can *fail* and *contribute* to the occurrence of each identified hazard. In this activity, firstly, we choose a particular *architectural component*, and identify potential *output deviations*, i.e., failures in component outputs, that can contribute to the occurrence of each identified hazard. We then specify the potential *causes* for the occurrence of each identified *output deviation* by analyzing potential *combinations* of component *internal failures* and *input deviations*. Such analysis continues while there remain *architectural components* to be analyzed. The component failure/faulty behaviour can be specified, using compositional techniques [7,8,9], as annotations in the SPL architecture model. Such annotations are stated as logical expressions, using **AND**, **OR**, and **NOT** operators, showing how *deviations* in component *output* ports can be raised either by component *internal failures and/or deviations* in the component *inputs*, or combinations of these *events*. In system safety analysis, component deviations may include unexpected *omission* of an output or unintended *commission* of output, or *incorrect* output *values*, or output being sent too *early* or *late* [8].

Considering *C1* software component in the **SC2** scenario, the causes of an *omission* of the *C1.out1* output can be: an *omission internal failure* of *C1* **OR** the occurrence of an *omission* failure at *C1.in1* **OR** *C1.in2* inputs, i.e., ***Omission-C1.out1 -> Omission-C1 OR (Omission-C1.in1 OR Omission-C1.in2)*** failure expression, stored in the**C1-SC2** component fault model library. Local component fault modeling can reflect either real characteristics or simply the design intention for the analyzed architectural components. In both cases the analysis is useful. At earlier stages, when components are under design and only design intentions are encoded, it is still possible to evaluate the suitability of the proposed design under the encoded intentions of the failure logic, fault propagation, fault mitigation, and fault tolerance of various architectural components. Late in the design, such analysis supports engineers in identifying weaknesses and taking decisions to improve the SPL architecture, e.g., by introducing components with improved characteristics or fault tolerant features. For hardware components, where failures are ***non-deterministic***, we specify the failure behaviour in terms of *values* of *reliability* attributes, e.g., *failure* and *repair* rates, which might change according to the targeted scenario. For example, we can assign that *C2* hardware component *failure rate* is *10e-7 per hour of operation in the **SC1** scenario*.

Compositional techniques allow the storing of the component failure behavior in a library, so that other components of the same type can further reuse it. Thus, we can encapsulate variation in component fault behaviors into fault model libraries. Each fault model library contains component failure expressions and failure modes addressing a specific usage scenario. A fault model library for a hardware component may contain values for *failure* and/or *repair* rates addressing a given scenario. The ***outputs*** of this activity are *component fault models* showing how components can contribute to the occurrence of system *hazards* in each targeted scenario. Different component failure data leads to different fault propagation's, i.e., combinations of component failures leading to the occurrence of system failures. Such variation propagates throughout fault trees and

[8] *Components that are isolated and protected in the architecture.*

FMEA artefacts. In order to support the systematic reuse of the system model enhanced with dependability information, i.e., HARA information and component fault models, we should manage the impact of design and usage context variations on dependability artefacts during *variability modeling*.

Integration of Variability Information:

The ***inputs*** for this activity are: the *SPL feature and context models*, along with the SPL *architectural*, *behavioral*, and *dependability models*. This activity extends the variability modeling (application variability modeling) step defined in traditional SPLE methods [18,19,20,42], aimed at establishing mapping links between *features* and their realization in the *architecture* model. This is to enable support for variability management in *dependability artefacts*. In this step, we define mappings linking system and usage context features to their realization in both architectural, behavioral, and dependability model elements. It is important to highlight that mapping links in the application variability model are useful to indicate which versions of components and their associated dependability information should be *included* in each *system variant* or in each *version* of a given variant.

Design and dependability base models can be specified with the support of compositional modeling languages and techniques [7,8]. Thus, to select design and dependability model elements and linking them to abstract representations defined in the SPL feature and context models, variant management tools have to communicate with compositional modeling tools. We can manage variability in system models enhanced with dependability information with the support of *extensions* to existing variant management techniques [11,32,35], e.g., BVR toolset [36]. This activity encompasses the following tasks: ***(i)*** specifying design and dependable-related *variation points* and their *variants* from the analysis of *interactions* between *system* and *usage context* features, and *scenarios* used to guide engineers during dependability analysis; ***(ii)*** mapping *design* variants (defined in the SPL feature model) to their realization in the SPL *architectural* and *behavioral* models by: defining *model elements* to be *included* (*replacement*) and/or *excluded* (*placement*) when each design variant is resolved during the product derivation process; and finally, ***(iii)*** mapping *dependable-related* variants (specified in the SPL feature and context models) to their realization in the dependability model by: linking each *variant scenario* considered during dependability analysis to the corresponding information about *HARA*, the *Allocation of Safety Requirements*, and *failure data* (fault model) associated with each variant-specific component.

A mapping link in an orthogonal variability model, which is the modeling technique adopted by the most variant management tools [11,32,36], comprises the tuple *M = (V, F, ME)*. *V* represents a variant, which provides a concrete instantiation of variable domain artefacts, e.g., architectural models, specified in a variation point (i.e. a place in the base model where variation can arise). *F* is a reference to a feature or a feature set specified in the SPL feature model (variability specification model). Finally, *ME* is a set of base model elements, e.g. architectural, behavioral and/or dependability model elements, which represent the realization of an SPL system/usage context feature or a feature set (*F*) in the base model.

A mapping link in the BVR variability model comprises *M' = (V, F, FS [Pme, Rme])*, which is a slight variation of the *M* tuple. An *FS* contains references to base model elements to be *excluded*, named *placement* elements (*Pme*), and to be *included*, named *replacements* (*Rme*), in a product-specific model during product derivation. Fragment substitution is a BVR toolset concept that refers to base model elements (ME) that should be excluded (*Pme*) and included (*Rme*) in a variant-specific model when an abstract feature (*F*) from the SPL domain model, representing a variant, is chosen. Thus, a *FS* establishes a traceability link between an abstract representation specified in the SPL feature model, and its implementation/realization in the base model. In our approach, we consider the specification of fragment substitutions (*FS*) with a **replacement** (*Rme*), and an **empty placement** (*Pme*) element in the variability model. Thus, references to base model elements to be included in a product-specific model are stored in replacement elements of mapping links (M') defined in the variability model.

Considering the hypothetical *FM* feature and *CM* context models, and product line dependability models (DM) as inputs to create the application variability model (*VM*), we have ***m1*** (*SC1*, *F1-CX1*, *FS-SC1-D (Pme[ ], Rme[HARA-SC1, S1-SC1, S2-SC1])*) mapping linking **SC1** variant, which represents the selection of *CX1* context and *F1* system domain features defined in the SPL feature and context models, to **HARA-SC1** hazard analysis information, and **S1-SC1** and **S2-SC1** component fault model libraries representing the realization of this variant in the dependability model. **F1-CX1** represents the *domain feature* associated with *FS-SC1-D* elements. By using this modeling strategy, there is no need to perform *substitutions* during the product derivation process. It is important to highlight that a *traceability matrix* showing the relationships between base model elements and their selection in each possible system variant/configuration, e.g., pure::variants [11] ***traceability matrix***, can support product line engineers in this activity.

The end of this step yields the enhanced *application variability model* that links features to their realization in both architecture, behavioral, and dependability model elements. The *application variability model* of a safety-critical SPL comprises a set of mappings (m1, m2...,mn) linking features, specified in the SPL domain model, to their realization in both design and dependability model elements. The variability information stored into the variability model is useful for variant management tools supporting the automatic/semiautomatic derivation of product-specific design models annotated with dependability information.

3.5 | DEPendable-SPLE: Application Engineering Phase

During the application engineering phase, both the SPL design and dependability artefacts, stored in an SPL assets repository following the previous steps, can be reused in the development of system variants that address customer-specific requirements. Thus, from the analysis of the product line feature/context models and customer-specific application requirements, SPL system and dependable-related features are chosen according to the targeted application requirements to derive the product/application feature model (i.e., variability resolution or instance model). Additional customer-specific system/product and usage context features, not predicted in the SPL domain modeling and design, can also be added to the application feature model, and to the SPL core assets repository. During the product derivation process, customer-specific design and dependability assets are generated, with the support of a variability management tool, e.g., BVR toolset[36], from the choices specified in the application/product feature model. Customer-specific system functions can be added to the generated variant-specific design.

The addition of customer-specific system functions and usage contexts may impact on the dependability analysis. Thus, variant-specific hazards and component failures can be identified during application of HARA and component fault modeling, and we can allocate application-specific safety requirements to mitigate their effects on the overall system safety/dependability. Finally, variant-specific fault trees and FMEA results can be generated, with the support of compositional dependability analysis techniques[7,8,9], from the reused HARA information and component fault models. With the exception of fault trees and FMEA synthesis, dependability analysis in the application engineering phase can be seen as *iterations* of the domain engineering phase. Thus, we only provide a brief description of *product hazard analysis* and *component fault modeling* to support the reader in better understanding our approach. We detail each DEPendable-SPLE application engineering approach activity in the following subsections.

3.5.1 | Application-Specific Requirements

Product-Specific Requirements: The ***inputs*** for this activity are the *product line feature and context models*, and *application requirements*. In this activity, design and dependable-related variants defined in the SPL feature and context models that address application requirements are chosen, and in some cases, application-specific requirements, not provided by the SPL, are added to the *product* feature and context models. The end of this activity ***yields*** *product feature and context models*. It is important to highlight that the addition of *product-specific* features may impact on both *product design* (*PL architectural customization*) and *dependability analysis*.

Identification of Candidate Scenarios for Product HARA:

The *product feature/context models*, product/application *architectural* and *behavioral* models, and the *analysts' domain knowledge* are inputs for this activity. After product derivation (i.e., PL architectural customization), we perform an analysis of *interactions* among chosen SPL *system* and *usage context* features, application-specific *system* and *usage contexts*, and *application-specific functions* added to the reused product architectural and behavioral models after product derivation. Such analysis is focused on identifying potential *scenarios, not predicted* in the domain engineering phase, that may impact on the overall *system safety/dependability*, e.g., with the emergence of application-specific system hazards and/or component failures. These scenarios can be used to guide engineers during product *hazard analysis* and *component fault modeling* activities by following the same steps defined in the domain engineering phase. It is important to highlight that the addition of application-specific system functions to the SPL design (architectural and behavioral models) can result in the emergence of different scenarios that may impact on the overall safety. These scenarios should be considered when guiding engineers through iterations of dependability analysis activities in the SPL domain engineering phase.

The ***output*** of this activity is a set of application-specific scenarios that may impact on overall safety. Emergent application-specific scenarios may cause disruption to the previous *assumptions* about *hazards* and *component* failures made by engineers in the domain engineering phase. There is little that can be done in these cases beyond storing *emergent assumptions* about *hazards*, *component faults*, and *safety requirements* in the SPL core assets, together with previous assumptions about dependability.

3.5.2 | Product Line Architecture Customization

Subsystem and component selection:

The SPL *feature* and *context models*, the enhanced *SPL variability model* with mapping links between *features* and their realization in *HARA information* and *component failure data*, the *product feature model*, and *SPL assets*, in this case, *architectural*, *behavioral*, and *dependability* models are ***inputs*** for this activity. The purpose of this activity is resolving, with the support of extensions of existing variability management tools, e.g., the BVR toolset, the variability specified in SPL architectural, behavioral, and dependability base models, and thus, deriving a product/variant-specific *system model* with *dependability information*. After deriving a product system model, functions intended to address application-specific requirements (stated in the product feature and context models) not provided by the SPL architecture can be added to the reused product design. These functions can be specified in the form of subsystems and/or components. The ***output*** of this activity is a product system model with dependability information, that is in some cases enhanced with application-specific system functions.

The addition of specific *functions* to the reused product design can result in different scenarios emerging that may impact on the product dependability. These scenarios should be considered by engineers during product dependability analysis. Application-specific functions can also provide feedback to the SPLE processes, enhancing the SPL architectural and/or behavioral models. The addition of application-specific system functions to the SPL design core assets may cause the emergence of different scenarios that may impact on the overall system dependability. These scenarios should be considered further by engineers in iterations of dependability analyses in the SPL domain engineering phase. Application-specific scenarios should be identified after the *selection* of SPL *subsystems* and *components* and *architectural customization*.

Product Hazard Analysis:

Application-specific scenarios, product *feature* and *usage context* models, product architectural and behavioral models, and analyst's domain knowledge are ***inputs*** for product hazard analysis. This activity should be performed by following the same steps defined for HARA in the domain engineering phase. Thus, we should perform *product HARA* for each identified application-specific scenario, which comprises application-specific product and usage context feature interactions, to identify combinations among component failures that may lead to the occurrence of system-level failures, which were not earlier identified in the domain engineering phase. Next, the risk for the overall safety posed by each application-specific hazard, in different usage scenarios, is estimated, based on the risk tolerability criteria defined in the targeted safety standard/considerations, e.g., SAE ARP 4754A *severity* and *likelihood*. The ***output*** of this activity is a list of product/application-specific hazards and their associated risk classification. Application-specific HARA information can be added to the SPL repository to be further available for reuse in the development (derivation) of other system variants from SPL core assets.

Allocation of Product Safety Requirements:

Application-specific scenarios and *HARA* information, along with *analysts' domain knowledge* are **inputs** for this activity. Thus, from the analysis of *product HARA*, functional safety requirements, e.g., redundancy, can be added to a variant-specific architecture model, and SILs can be allocated to eliminate or minimize *hazard* effects on overall safety. In the same way as in the domain engineering phase, SILs should be allocated to each *product-specific hazard* according to their *risk classification*. A set of application-specific *functional safety requirements*, i.e., *system functions* aiming at mitigating *system-level failures*, and *SILs* allocated to *system hazards* are the ***outputs*** of this activity. Additionally, *SILs* allocated to application-specific hazards are further *decomposed* to contributing *component failure modes*. SIL decomposition can be performed for a particular *system variant* with automated support of SIL decomposition genetic and meta-heuristic algorithms [8,41].

The decomposition of SILs, allocated to application-specific *hazards*, to contributing *components* and their *failure modes* early in the design, can support engineers on the specification of *cost-effective* application/product *development processes* according to the *level of integrity* assigned to subsystem components. Thus, the development process of two different variant-specific subsystem components with different levels of integrity do not need to address the requirements posed by the *most stringent* level of integrity assigned to a given component. Application-specific *functions* and allocated *safety integrity levels* can be added to the SPL repository to refine the SPL design and ensuring the safe operation of components across a range of different system variants not predicted in the product line design.

Product Component Fault Modeling:

The ***inputs*** for this activity are application-specific scenarios and HARA information. From the analysis of the identified *hazards* that can be raised in a specific *system variant* and its associated *usage contexts*, assumptions can be made about how application-specific architectural components, i.e., *reused* and *application-specific* assets, can fail and contribute to the occurrence of each *emergent hazard* (identified during application HARA). In this step, we analyze each application-specific component to identify potential *output deviations* that can contribute to the occurrence of each identified application-specific hazard, and their *causes*, i.e., combinations among component *internal failures* and *input deviations*,in the same way as in the domain engineering phase. Such analysis continues while there remain application-specific *components*. At the end of *product component fault modeling*, we obtain a set of application-specific component fault models, and the *reused* domain *component fault models* are *enhanced/updated* with product-specific dependability information. Thus, the ***outputs*** of *Product Dependability Analysis* are enhanced application-specific *design* and *dependability* models, and in some cases, feedback to the safety-critical SPLE processes. Thus, enhancing the SPL *architectural*, *behavioral*, and *dependability* (i.e, *HARA information* and *component fault models*) models stored in the DEPendable-SPLE repository (see Figure 2).

3.5.3 | Product Testing

Fault Trees and FMEA Synthesis:

The *reused* product-specific *architectural and behavioral models*, enhanced with specific *dependability information*, are the ***inputs*** for performing the synthesis of fault trees and FMEA results with the support of compositional techniques [7,8,9]. *Fault trees* and *FMEA* results can be automatically generated, with the support of compositional techniques, from the *reused* and *product-specific* dependability information produced during *domain* and *application* engineering phases. The accuracy of the generated product-specific *fault trees* and *FMEA results* is dependent on whether both domain and application *dependability analysis* activities were performed with awareness of the impact of *design* and *usage context variations* on overall safety. The end of this activity ***yields*** application-specific fault trees and FMEA results that can be used to demonstrate that the architecture of a particular system/product variant addresses safety/dependability requirements.

4 | CASE STUDY

This section presents the application of the DEPendable-SPLE approach in the Tiriba Flight Control System and Software Product Line (TFC-SPL). In subsection 4.1, we present an overview of the TFC-SPL, with focus on domain modeling and design, without going into details concerning dependability aspects. In subsection 4.2, we illustrate the dependability approach steps and integration of variability information in the domain engineering phase. Finally, in subsection 4.3, we present dependability steps regarding the application engineering phase.

4.1 | Tiriba Flight Control Product Line

TFC-SPL is part of the Tiriba UAV avionics SPL [43] (see Section 2), comprising a control subsystem with the following goals: to start the flight mode (i.e., which can be direct, stabilized, or autonomous), processing and setup of flight commands, keeping flight conditions, and executing commands sent by the navigation subsystem. Although Tiriba was originally designed in MATLAB Simulink [44], to illustrate the integration of variability management and compositional dependability analysis techniques, TFC-SPL design and dependability models were specified in OSATE AADL (Architectural Analysis and Description Language) and AADL Error Annex [7]. BVR toolset [36], and a BVR enabler adapter to OSATE AADL & Error Annex developed by the authors were used to support variability management in both TFC-SPL design and dependability models.

4.1.1 | Tiriba Product Line Domain Modeling

TFC-SPL was designed following an extractive strategy by analyzing the original Tiriba Flight Control subsystem [25] Simulink model. Figure 3 shows the interconnected TFC-SPL feature and context models. We created TFC-SPL domain models by following Lee and Kang [26], Hartman and Trew [28] multi-perspective feature modeling approaches and their refinements [29,30]. These modeling approaches allow separating the specification of *system* features from *usage context* features, and a more clear understanding of their relationships.

TFC-SPL system feature model (Figure 3 (left)) comprises: the *Pilot Mode*, the *Landing Type*, and *Navigation Services* variation points. *Landing Type* variation point encapsulates variation on the *UAV landing* capability, which can be: via activation of a *Parachute* to smooth the impact on the *ground* and avoid potential damage to the UAV when landing in an area where a runaway is not available, *Autonomous*, i.e., the UAV is pre-programmed to land in a specific area, or via *Remote Control* by receiving and executing *landing commands* sent by an human operator from a *ground control station*.

Navigation Services variation point encapsulates variation on the Tiriba UAV *mission behavior*. Thus, the UAV can abort a mission segment (*Mission Abortion* optional feature) or perform a simulation (*Entry Segment Sim* feature), whenever the UAV starts a new mission segment, to find the most suitable maneuver to switch between two mission segments. The UAV *route* can be adjusted whenever the aircraft deviates more than a certain *threshold* (limit) from the planned *mission route* (*Route Correction*). The UAV can also *return* to specific positions where a picture was not taken during the mission when the *Route Tracking* feature is chosen. Finally, the *Pilot Mode* variation point contains four pilot mode options/variants: *Manual Pilot* is mandatory, *Assisted Pilot*, *Autonomous Pilot*, and *Autopilot* are optional. In the *Manual Pilot* mode, a human operator send commands to the unmanned aircraft vehicle (UAV) from a ground control station.

In the *Autopilot* mode, the UAV executes a pre-defined route. The *Assisted Pilot* mode allows the operator to send commands to the UAV configured with *Autopilot* mode. The *Autonomous Pilot* mode allows the UAV to perform actions according to its current environmental conditions captured by pressure sensors. *Assisted Pilot*, *Autonomous Pilot*, and *Autopilot* optional features can be combined in several different ways, allowing seven different flight control system variants.

TFC system/product variants can operate in a range of different usage contexts defined by combining *Airspace*, *Application*, and *UAV Size* variation points and their variants. Figure 3 (right) shows an excerpt of the TFC-SPL context model [43]. A Tiriba flight control system variant can operate in an *Uncontrolled* or *non-segregated* airspace. This refers to the operation of a UAV outside of a *Controlled* or *segregated* airspace, which covers airspace dimensions allocated for exclusive use to specific users [27]. A system variant operating in a segregated/controlled airspace must include the *Mission Abortion* optional system feature, manual and autonomous pilot feature, along with route tracking and route correction mission controller capabilities. A system variant operating in an uncontrolled airspace must include *Entry Segment Simulation feature*.

A Tiriba flight control system variant can be deployed into a *Small UAV* (a UAV weighing less than 5 kg), or in a *Light UAV*, a UAV with weight ranging from 5 to 20 kg. The *Parachute Landing* capability is excluded from a system variant when deployed into a Light UAV and operating in an uncontrolled airspace. A Tiriba system variant can be used for civilian applications, e.g., detection of crop diseases in *agriculture*, topographical surveys and traffic monitoring, urban planning, and power transmission line inspection in the *environment monitoring* category, or for defense applications.

4.1.2 | Tiriba Flight Control Product Line Design

Variability specified in the TFC-SPL *feature* and *context* models propagates throughout the design. The Tiriba Flight Control (TFC) product line architecture encompasses 4 subsystems and 14 components, which are composed by 252 model elements and subcomponents. Figure 4 shows an

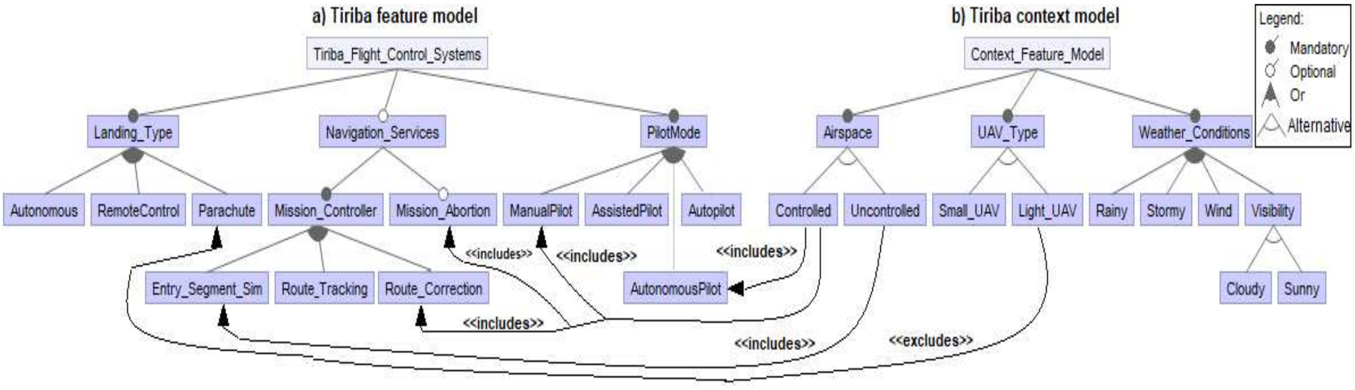


FIGURE 3 Tiriba feature model (left) and context feature model (right).

excerpt of the Tiriba Flight Control SysML main block diagram. The flight control mode function, aimed at initiating different flying modes, is represented by the *Mode Switcher* component. The flight and set commands functions are supported in the architecture by the *PWM Decoder*, *Fail Safe Controller*, and *Command Switch* for take-off and landing operations. The purpose of the third flight control function is the provision of navigation operations for the UAV in pre-defined flight conditions, and is represented in the TFC architecture by the Autopilot component.

The *Mode Switch* subsystem component encapsulates the *Pilot Mode* variation point shown in Figure 3 (left), whilst the *Command Switch* component encapsulates the variation point inherent to the source from the pilot commands, e.g., *manual pilot* or *autopilot* subsystems, sent to the UAV. The *Basic Command Processor* (BCP) subsystem and its ports represent the realization of the *Autonomous Pilot* mode feature. The PWM (Pulse-Width Modulation) Decoder component output port connected to *Command Switch* block represents the realization of the *Manual Pilot* mode feature in the design. The realization of *Autopilot* feature in the design is given by: *Autopilot*, *Flight Control Mixer* (FCM), and *Fail Safe Controller* (FSC) subsystem components, *PWMDecoder.FlightControls* output port connected to *FlightStabilizer* and *Command Switch* model components, and *FlightStabilizer.AutopilotSettings* output port connected to *Assisted Mode Switch* component. Finally, the *Mode Switcher* subsystem output ports which are connected to *Assisted Mode Switch* and *Command Switch* components represent the realization of the *Assisted Pilot* mode feature.

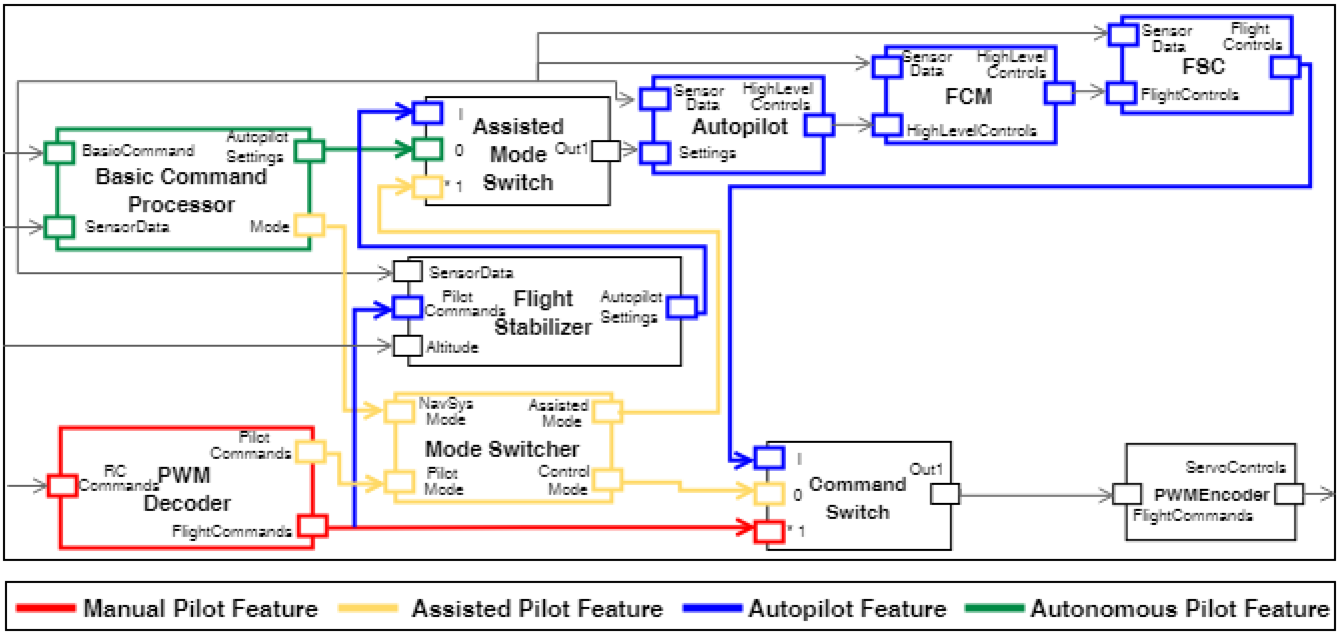


FIGURE 4 Feature realization in the Tiriba flight control architectural model.

TFC-SPL variation points and their variants specified during domain modeling propagate throughout the product line architecture model. Thus, when we choose *Manual Pilot* and *Autonomous Pilot* system features (TFC-MAT system variant) and *Controlled* airspace context feature, *Basic Command Processor* and *PWM Decoder* subsystems, their ports (except *BCP.Mode* and *PWMDecoder.PilotCommands* output ports) and connections, shown in Figure 4, should be included in a TFC variant-specific architecture model. On the other hand, *Assisted Pilot*, *Autopilot*, *Autonomous Pilot*, and *Manual Pilot* features, i.e., the all pilot modes (TFC-ALL) system variant operating in an *Uncontrolled* airspace, are materialized in the architecture by all Tiriba flight control subsystems, components, their ports and connections (see Figure 4). Still in the TFC-SPL, the selection of variants from *Pilot Mode* and *Airspace variation points* impacts on the derivation of redundant and non-redundant components in a variant-specific architecture model. Finally, architectural variation inherent to TFC-MAT and TFC-ALL system variants along with variation in the *usage context* are further propagated throughout the Tiriba Mission Controller behavioural model expressed in a finite state machine.

Variability in the selection of Tiriba mission-related features specified in Figure 3(left) are propagated throughout the Tiriba mission controller state machine shown in Figure 5, which defines the mission controller configuration using a mechanism of *state transitions* conditioned to *state variable* values that define variability. Thus, when the *Entry Segment Simulation* mission-related system/functional feature is chosen, a *simulation* is performed whenever the UAV starts a new mission segment (see Figure 5(left)), in order to find out the suitable approach for switching between two mission segments. When the *Route Correction* (i.e., *Feather Threshold*) functional feature is selected, the UAV route is adjusted whenever the aircraft deviates more than a certain *threshold* (limit) from the planned mission route. The realization of this feature is expressed by the *correction start* state transition in the Tiriba FSM from Figure 5 (left). Finally, when the *Route Tracking* (i.e., *Failure Handler*) feature is selected, the UAV is able to return to specific positions where a picture was not taken during the mission, which is dispatched by the *good simulation* state transition in Figure 5 (left).

The activation or deactivation of Tiriba mission controller functional features is defined by alternative flows with *Boolean* conditional *variables* (see Figure 5 (right)), which allow enabling or disabling FSM *flows* and *states* according to the feature selection. Thus, for each one of the aforementioned mission-related features, there is a variable whose value defines which FSM *states* and *transitions* will take place in the final product.

The *SimEnable Boolean* variable controls the activation/deactivation of the behaviour related to the *Entry Segment Simulation* feature. When this feature is selected, i.e., when the TFC-ALL (all pilot modes) system variant and *uncontrolled* airspace context variant are chosen, the *SimEnable* variable is set *true* (see Figure 5 (right)). On the other hand, *SimEnable* is set *false* when the *Entry Segment Simulation* feature is not selected. The same is valid for selection/activation and deselection/deactivation of the *Route Correction* and *Route Tracking* functional features.

It is important to highlight that *usage context* features may have influence in the selection of system/design features that impact on the Finite State Machines, changing the system behaviour. Thus, when *uncontrolled* airspace usage context and TFC-ALL system variants are chosen, the *SimEnable* state variable from Figure 5 (right) is set *true*, activating the transition to the *Simulating* state (see Figure 5 (left)) in a variant-specific mission con-

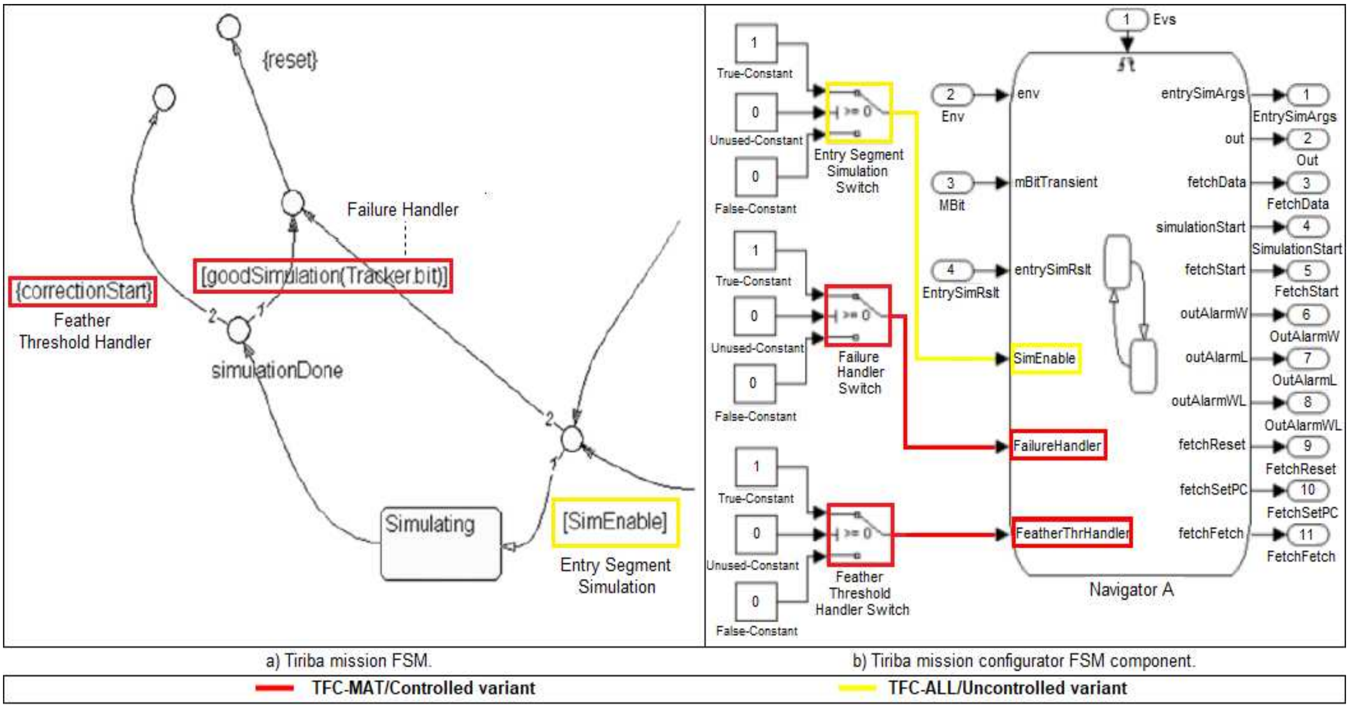


FIGURE 5 Tiriba mission controller finite state machine (left) and mission configurator FSM component (right).

troller FSM. When the *controlled* airspace context and TFC-MAT (manual and autonomous pilot) system variants are selected, *FeatherThrHandler* and *FailureHandler* state variables are set *true*, activating both the *correction start* and *good simulation* state transitions illustrated in Figure 5 (left).

4.2 | TFC-SPL: Dependability in Domain Engineering

In this phase, we initially analyzed interactions between Tiriba system and usage context features to identify scenarios to guide dependability analysis. On the basis of the identified scenarios, we performed TFC-SPL hazard analysis and component fault modeling. Finally, we linked Tiriba domain variants to their realization in both Tiriba SPL design and dependability model elements in the Tiriba application variability model.

4.2.1 | Identification of Scenarios and Tiriba Hazard Analysis

From the analysis of the TFC-SPL *system* and *usage context* variants specified in the feature and context models shown in Figure 3, a range of candidate scenarios can be derived. The composition of *pilot mode product* variants and *usage context* variants leads to 84 different TFC system variants. However, since it would be prohibitive performing dependability analysis covering all these variants, only Tiriba Flight Control *manual* and *autonomous* (TFC-MAT) and *all pilot modes* (TFC-ALL) system variants, respectively operating in *Controlled* and *Uncontrolled* airspace usage contexts, together with the analyst's domain knowledge, were considered to perform Tiriba dependability analysis. We performed TFC-SPL *HARA* with the support of domain experts, by considering TFC-MAT and TFC-ALL system variants and their usage contexts, which were analyzed from the perspective of the SAE ARP 4754A Risk Assessment process.

Table 1 shows an excerpt of TFC-SPL *hazard analysis and risk assessment*. Variation in the *causes* of the *No pilot commands* and *Value pilot commands* hazards, and in the *risks* that they pose for overall safety, were identified in both of the two aforementioned system variants (see Table 1). The causes for the *no pilot commands* hazard are *omission* failures in *FailSafeController* (FSC) and *PWMDecoder* component outputs when the TFC-MAT system variant and *controlled airspace* usage context are chosen. On the other hand, omission failures in the *FSC*, *ModeSwitcher*, and *PWMDecoder* component outputs are the *causes* for the occurrence of the same hazard when the TFC-ALL system variant and *uncontrolled airspace* usage context are selected. Such variation can also be found in the causes of *incorrect value of pilot commands*, i.e., *value pilot commands* hazard, which may change according to the targeted system and usage context variants (see Table 1). Variation in the TFC-SPL hazard analysis further propagates throughout the *risk assessment*.

In the TFC-SPL *risk assessment*, different values for *likelihood* (probability of occurrence) and *severity* reliability attributes were assigned to classify the risk posed by the *no pilot commands* and *value pilot commands* hazards, according to the targeted *system* and *usage context* variants. Thus, the probability of occurrence of both *omission of pilot commands* (i.e., no pilot commands hazard) and *incorrect pilot commands* (i.e., value pilot commands) are respectively ***10e-9*** and ***10e-7*** per hour of operation with ***catastrophic*** and ***hazardous*** severity when the TFC-MAT system and *controlled airspace* usage context variants are chosen. On the other hand, the probability of occurrence of both hazards are respectively ***10e-7*** and ***10e-5*** per hour of operation with ***hazardous*** and ***major*** severity when the TFC-ALL system variant and *uncontrolled airspace* are chosen. Variation in the assignment of values to hazard *severity* and *likelihood* may impact on the allocation of functional safety requirements, and allocation and decomposition of DALs to avoid or minimize *hazard* and/or *component failure* effects on the overall safety of TFC-SPL components.

TABLE 1 Tiriba flight control product line HARA and allocation of safety requirements.

	Hazard Analysis		**Risk Assessment and Allocation of Safety Req.**		
System Variant	**Hazard Defn.**	**Hazard Causes**	**Severity**	**likelihood**	**DAL**
TFC-MAT/ Controlled	No pilot commands	Omission-FSC.filteredControls AND Omission-PWMDecoder.flightControls	Catastrophic	10e − 9	A
TFC-ALL/ Uncontrolled	No pilot commands	Omission-FSC.filteredControls AND Omission-PWMDecoder.flightControls AND **Omission-ModeSwitcher.controlMode**	**Hazardous**	**10e-7**	**B**
TFC-MAT/ Controlled	Incorrect pilot commands	Value-FSC.filteredControls AND Value-PWMDecoder.flightControls	Hazardous	10e − 7	B
TFC-ALL/ Uncontrolled	Incorrect pilot commands	Value-FSC.filteredControls AND Value-PWMDecoder.flightControls AND **Value-ModeSwitcher.controlMode**	**Hazardous**	**10e-5**	**C**

4.2.2 | Allocation and Decomposition of Safety Requirements in the Tiriba SPL

After estimating the *risk posed* by each identified hazard, *functional safety requirements*, and *safety integrity requirements*, in terms of *DALs*, were allocated to mitigate Tiriba hazard effects. Following the analysis of the TFC-SPL risk assessment, we allocated different functional safety requirements, expressed in terms of architectural decisions, according to the chosen Tiriba flight control *system* and *usage context* variants. A *Redundant* Tiriba control system architecture should be adopted when the *controlled airspace* usage context is chosen. On the other hand, a *Non-Redundant* architecture is sufficient to address the safety requirements when the Tiriba UAV is intended to operate in an *uncontrolled airspace*[43].

Based on the analysis of the risk assessment (Table 1), *DALs* with different degrees of stringency were also assigned to mitigate *hazard* effects in different TFC system variants (see column **DAL** in Table 1). Thus, we assigned **DAL B** to mitigate the effects of the occurrence of the *value pilot commands* hazard in the TFC-MAT system variant operating in a *controlled airspace*. On the other hand, **DAL C** is sufficient to mitigate the effects of this hazard when the TFC-ALL system variant operating in an *uncontrolled* airspace is chosen.

Variation in the DALs allocated to mitigate hazard effects in both Tiriba system variants has a direct impact on the development processes to be enacted to comply[9] with safety standards/considerations in order to achieve the *safety certification*[3] of an individual *system variant*. Thus, expensive objectives, e.g., *performing the aircraft/system functional hazard assessment* ***with independence***[10], prescribed by SAE ARP 4754A to achieve **DAL A**, should be enacted to mitigate the effects of the occurrence of the *value pilot commands* hazard when the TFC-MAT system variant operating in a *controlled airspace* is chosen. On the other hand, when the TFC-ALL system variant operating in an *uncontrolled airspace* is chosen, performing the aircraft/system functional hazard assessment ***without independence*** is sufficient to mitigate the effects of the same hazard. This reduces development costs in comparison with the costs and effort for producing safety assets to certify the TFC-MAT system variant.

The DALs allocated to mitigate the effects of the occurrence of ***TFC hazards*** can be further decomposed to contributing components and their associated failure modes identified during component fault modeling. We performed DAL decomposition for each Tiriba system variant with the automated support of meta-heuristic optimization algorithms[8]. These algorithms implement aerospace SAE ARP 4754A[4] rules for allocating DALs to functions and decomposing them throughout the items. Rules allow downgrading the DALs assigned to functions (*at the system level*) to the items (*at the component level*) based on the *independence* at *requirements*, *implementation*, or *hardware deployment* levels[41]. In the allocation and decomposition of DALs for the Tiriba case study, we assumed that the components are isolated and protected in the architecture.

Table 2 shows the decomposition of DALs allocated to the ***No pilot commands*** and ***Value pilot commands*** hazards (see Table 1) to the *Barometric Processor* (BP) and *PWM Decoder* components and their failure modes in both TFC-MAT and TFC-ALL system variants. DALs with different degrees of stringency were assigned to *mitigate* the effects of different failure modes of a given component in the same system variant. For example, **DAL A** and **DAL E** were respectively assigned to mitigate the effects of ***OFailure1*** (*omission*) and ***VFailure1*** (*value*) failure modes on the overall dependability of PWM Decoder subsystem in the TFC-MAT *system variant* (see column ***FM-DAL: MAT*** from Table 2). Such variation may impact on the *DAL* that should be assigned to *ensure* the *safe* use of the *PWM Decoder* ***component*** in the TFC-MAT ***system variant***.

We determine the DAL that should allocated to ensure the safe use of a given SPL component in a particular system variant, e.g., TFC-MAT, by analyzing the DALs allocated to each *failure mode* of the given component. The most *stringent DAL* allocated to a *failure mode* of a component is the required *safety requirement* to guarantee its safe use in the given system variant. Considering **DAL A** and **DAL E** respectively allocated to mitigate the effects of the *PWM Decoder* omission and value failures in the TFC-MAT system variant, **DAL A** should be assigned to ensure the safe use of *PWM Decoder* component in this variant (see column ***DAL:MAT*** from Table 2). On the other hand, a less stringent **DAL C** is sufficient to mitigate the effects of the occurrence of failures in the *Barometric Processor* subsystem in the TFC-MAT system variant.

Variation in the DALs assigned to **different** Tiriba SPL components in the ***same*** system variant may *impact* on the structure of *development processes* to be enacted to ensure the safety of a component in the given system variant. Different ***objectives*** should be addressed and different ***activities*** should be performed to produce ***artefacts*** to ensure the safety of the different components in a given system variant. By analyzing the DALs allocated to mitigate component failures in the TFC-MAT system variant (see Table 2), it can be seen that the *PWM Decoder* is a highly critical component with **DAL A**. Thus, expensive safety objectives with *independence*, e.g., *SAE ARP 4754A*[4]*: aircraft functional hazard assessment*, and *DO-178C*[3]*: verification of additional code*, should be addressed. On the other hand, less critical components, e.g., the *Barometric Processor* a **DAL C** component, demand less stringent safety objectives that do *not require independence*.

[9] *Compliance checks are only sampling events. For example, compliance to DO-178C safety considerations for airborne systems is only to verify if the implementation of a given set of requirements is correct. This is important because if there is a fundamental flaw in the safety assessment process, safety requirements may not be complete and correct, thus, leading to a faulty system even at DAL A.*

[10] *Independence: separation of responsibilities which ensures the accomplishment of objective evaluation. For software verification activities, e.g., hazard analysis, independence is achieved when the activity is performed by a person(s) other than the developer of the item under analysis*[3].

TABLE 2 Variability in the DAL decomposition throughout components and their failure modes in different system variants.

Component	Failure Mode	FM-DAL: MAT	DAL: MAT	FM-DAL: ALL	DAL: ALL	SPL: DAL
Barometric Processor	OFailure1	C	C	C	**C**	**C**
	OFailure2	C		C		
PWM Decoder	**OFailure1**	A	A	**C**	**C**	**A**
	OFailure2	-		**C**		
	VFailure1	E		**C**		
	VFailure2	-		**C**		

- : failure mode is absent in the component in a particular system variant.

The definition of development processes according to the targeted level of the integrity of each TFC-MAT system component help to avoid ***unnecessary costs*** for achieving ***compliance with standards*** without compromising dependability/safety. In this way, considering TFC-MAT components and the DO-178C safety standard, all ***DO-178C objectives*** (66) were only assigned to ensure the safety of the **DAL A *PWM Decoder*** subsystem. On the other hand, the assignment of 57 ***DO-178C objectives*** were sufficient to ensure the safety of the **DAL C *Barometric Processor*** subsystem instead of allocating the remainder **DAL B** and **DAL A** *objectives*, which would increase the development *costs* of the ***Barometric Processor*** subsystem in the TFC-MAT system variant.

Variation in the DALs allocated to the Tiriba flight control *hazards* in different variants propagates to the DALs allocated to mitigate the effects of contributing component failure modes. DALs with different degrees of stringency were assigned to mitigate the effects of the *PWM Decoder* subsystem failure modes according to the targeted *system* and *usage context* variants. **DAL C** is sufficient to mitigate the effects of the occurrence of *OFailure1* failure mode on the overall safety of the *PWM Decoder* in the **TFC-ALL** system variant. On the other hand, we assigned a stringent **DAL A** to mitigate the effects of the occurrence of this failure mode in the **TFC-MAT** system variant. Thus, the **DAL** allocated to a given component failure may change according to the targeted *system* variant. Such variation is further propagated to the assignment of DALs to the *PWM Decoder component* in different *system variants*. Thus, a stringent **DAL A** was assigned to ensure the safety of *PWM Decoder* component in the **TFC-MAT** system variant (see column **DAL:MAT** from Table 2). On the other hand, a less stringent **DAL C** is sufficient to mitigate *PWM Decoder* failure effects in the **TFC-ALL** variant (see column **DAL:ALL** from Table 2). Such variation may impact on the structure of ***development processes*** to be enacted to ensure the safety of the ***PWM Decoder*** component in different ***system variants***. Consequently, engineers must address different ***objectives***, performing different ***activities*** for producing ***artefacts*** to achieve the ***PWM Decoder*** component ***safety approval*** in each TFC system variant.

The analysis of the DALs assigned to the Tiriba SPL components in different system variants may support engineers in identifying the safety requirements that should be allocated to ensure the safe use of components across the SPL, i.e., across a set of different system variants relevant for the stakeholders. We perform such analysis on the basis of the following principle: the most stringent DAL assigned to a given failure mode of a Tiriba SPL component across multiple system variants is the DAL that should be assigned to ensure the safe use of a component across the analyzed system variants, in this case, TFC-MAT and TFC-ALL. Thus, from the analysis of the DALs assigned to the ***PWM Decoder*** component in different Tiriba system variants, i.e., **DAL A** in **TFC-MAT** and **DAL C** in **TFC-ALL**, it is possible to infer that **DAL A** should be assigned to this component to ensure its safe use across the SPL.

Although the most stringent **DAL A** was assigned to the ***PWM Decoder*** subsystem in only one TFC variant, and less stringent **DAL C** on other variant, **DAL A** was assigned to that component to avoid ***loss*** and ***unnecessary budget***, i.e., additional *re-verification*, *validation* and *testing* effort, in case the *PWM Decoder* is further used in ***most expensive*** variants. From such analysis, we can obtain the decomposition of DALs assigned to TFC hazards across the SPL. Early in the design, it can support engineers on structuring a ***cost-effective*** development process for the ***Tiriba Flight Control product line***. A detailed discussion about allocation and decomposition of safety requirements in safety-critical software product line design can be found elsewhere[6].

4.2.3 | Tiriba SPL Component Fault Modeling

In the TFC-SPL, different *component failures* may contribute to the occurrence of each identified *hazard* in different *TFC variants* and *usage contexts*. During the Tiriba component fault modeling, we specified 106 *failure expressions*, stored in *fault model libraries*, which were added to 47 Tiriba flight control model elements.

Table 3 shows an excerpt of the Basic Command Processor (BCP) component fault models. Different *output deviations* may occur in this component in different Tiriba system variants. *Omission* of both the ***AutopilotSettings*** and ***Mode*** component's ***output ports*** may be raised in the ***BCP***

TABLE 3 An excerpt of Tiriba component fault analysis and modeling.

		Component Failure Data	
System Variant	**Component**	**Output Deviation**	**Failure Expression**
TFC-MAT/ Controlled	BCP	Omission-*AutopilotSettings*	OFailure1 OR (Omission-*BasicCommand* **OR** Omission-*SensorData*)
TFC-ALL/ Uncontrolled	BCP	*Omission-AutopilotSettings*	OFailure1 OR (Omission-*BasicCommand* **AND** Omission-*SensorData*)
		Omission-Mode	**OFailure2 OR (Omission-*BasicCommand* AND Omission-SensorData)**

component, contributing to the occurrence of *hazards*, when the **TFC-ALL** system variant operating in an **uncontrolled** airspace is chosen (see column **Output Deviation** from Table 3). On the other hand, only an *omission* of the ***AutopilotSettings output port*** contributes to the occurrence of *hazards* when the **TFC-MAT** system variant operating in a **controlled** airspace is chosen. Additionally, different combinations among ***component input deviations*** and ***internal failures*** contribute to the occurrence of ***Omission-AutopilotSettings*** output values in both **TFC-MAT** and **TFC-ALL** system variants (see column **Failure Expression** in Table 3).

We specified the causes of an *output deviation* in a *failure expression* using logical operators (AND, OR, NOT) describing how combinations of the *internal* and *input failures* of a component may lead to the occurrence of an *output deviation*. The occurrence of an ***internal omission failure*** in the BCP component **OR** ***omission failures*** in **both** the BCP ***inputs*** can raise an ***Omission-AutopilotSettings*** output deviation in the **TFC-ALL** variant. Conversely, an ***internal omission failure*** in the BCP **OR** the occurrence of an ***omission failure*** in ***one of the*** BCP ***inputs*** may raise an ***Omission-AutopilotSettings*** in the **TFC-MAT** system variant. Thus, when variability in the dependability assets is solved for the TFC-ALL system variant, only the component fault model associated with this variant is included in a variant-specific dependability model. Such variation is then propagated throughout variant-specific *fault trees* and *FMEA* artefacts. In order to support the systematic reuse of the TFC-SPL dependability assets, i.e., HARA information and component fault models, we manage the impact of ***design*** and ***usage context*** variations on dependability information during *variability modeling*.

4.2.4 | Integration of Dependability Information into TFC-SPL Variability Model

We specified the TFC-SPL domain *feature* and context models, and the application *variability model* with the support of the BVR[36] variability management toolset, and *AADL Error Annex enabler adapter* for the *BVR toolset* developed by the authors. Whereas variability management techniques available in the literature do not provide native support for managing variability in dependability base models (i.e., system models enhanced with dependability information), in this paper, the authors built an adapter to the BVR toolset[36] for establishing a link between the BVR realization editor and OSATE AADL model editors. This, enables BVR for supporting variability management in AADL design base models enhanced with dependability information produced using OSATE compositional modeling toolset[7].

The AADL BVR enabler adapter extends OSATE AADL & Error Annex model editors to enable the BVR tool to communicate with ***OSATE-based*** model editors. This is needed for allowing BVR to manage variability in both AADL structural/architectural, behavioral, and dependability base models. Since the BVR toolset is built upon the Eclipse Modeling Framework[45] platform, the adapter was implemented as an Eclipse-based plugin. A discussion about the AADL enabler adapter for BVR tool developed by the authors is outside the scope of this paper. Details about how to create an ***adapter*** to the BVR tool, and ***configuring*** a BVR variability model for a particular ***software product line*** can be found elsewhere[36]. We have defined BVR *fragment substitutions* (***FS***) (*see sub-section 3.4.2*) to show how variability in the TFC product line AADL *design* and *error* models are resolved when *TFC-MAT/Controlled* and *TFC-ALL/Uncontrolled variants* are chosen.

Table 4 illustrates BVR *replacement* elements, and *fragment substitutions* (i.e., ***mapping links***) associated with **TFC-MAT/Controlled** and **TFC-ALL/Uncontrolled** system/context variants specified in the BVR variability model for the TFC product line. Each ***fragment substitution*** contains an **empty placement** element, and a **replacement** element with references to the **design** and **dependability** base model elements that should be included in a Tiriba variant-specific system model when a domain ***variant*** is chosen. The table columns respectively represent: ***Variation Point*** (i.e., a ***variation point*** specified in the SPL domain model), *Fragment Substitution* (i.e., a ***variant*** associated with a ***variation point***), *Fragment Type* (in this case only ***replacements***), *HARA Information*, and *Component Failure Data*.

TABLE 4 Pilot mode/usage context variants and their realization in the Tiriba dependability model.

Variation Point	Fragment Substitution	Fragment Type	Dependability Information	
			HARA Information	Component Failure Data
Pilot Mode/ Airspace	TFC-ALL/ Uncontrolled	*Replacement*	*ALL-NoPilotCommands* *ALL-ValuePilotCommands*	*ALL-PWD-Fault-Model* *ALL-MSW-Fault-Model* ... *ALL-BCP-Fault-Model*
	TFC-MAT/ Controlled	***Replacement***	***MAT-NoPilotCommands*** ***MAT-ValuePilotCommands***	***MAT-PWD-Fault-Model*** ***MAT-BCP-Fault-Model*** ... ***MAT-MSW-Fault-Model***

Table 4 shows an excerpt of ***mappings*** linking ***dependable-related domain variants*** to their realization into ***dependability model elements***, defined in the TFC-SPL variability model. Thus, when the **TFC-MAT** system variant operating in a **controlled** airspace usage context is chosen, *HARA information* and *component fault models* associated with other TFC system variants are removed from the *dependability model*. On the other hand, as specified in the *replacement element*[11], *HARA information* and *component fault models* associated with the **TFC-MAT** system variant, e.g., the***MAT-No-Pilot-Commands*** hazard and the ***MAT-BCP-Fault-Model*** should be included in the final product dependability model. Later, we created a *fragment substitution* related to the **TFC-MAT/Controlled *variant*** by combining an ***empty placement*** and ***replacement*** elements. We also have created a ***replacement*** element with references to HARA information and component fault models that should be included in the final product dependability model when TFC-ALL/Uncontrolled variant is chosen.

The final TFC-SPL variability model comprises: 8 *fragment substitutions*, 1 ***empty placement***, and 8 *replacement* elements. We defined **four** fragment substitutions to specify the realization of *system features* in both the Tiriba SPL *architectural* and *behavioural* models, and four fragment substitutions were defined to specify the realization of *dependable-related* and *usage context* features in the SPL dependability model specified as ***dependability annotations*** in the TFC-SPL ***AADL design***.

4.3 | TFC-SPL: Application Engineering

In this phase, we defined application feature and context models for two different Tiriba system variants. We input these models to the BVR toolset supporting the derivation of variant-specific system models enhanced with dependability information. We performed iterations of dependability analysis steps defined in the domain engineering phase for identifying application-specific scenarios that may impact on system dependability, along with potential hazards and component failures that can emerge from these scenarios.

4.3.1 | Tiriba Product Requirements Engineering and Architecture Customization

We performed product requirements engineering from *requirements* for ***agriculture*** and ***environment monitoring*** applications. For each application, we have chosen the Tiriba flight control *system* and *usage context* features (see Figure 3) that addresses its *requirements*. Thus, we have chosen ***manual***, ***autonomous***, ***assisted***, and ***automatic pilot*** system features, and the ***uncontrolled*** airspace context feature that address ***agriculture application*** requirements (TFC-ALL system variant). We also selected ***manual*** and ***autonomous pilot*** system features and the ***controlled*** airspace context feature to address ***environment monitoring*** application requirements (TFC-MAT system variant). During the specification of *feature* and *context* models for these two applications, we identified *Weather Conditions* variant-specific usage context features such as *rainy*, *stormy*, *wind*, and *visibility*, which can be *cloud* or *sunny*, that may impact on the system dependability properties. Since *weather conditions* features may impact on *dependability* properties of other system variants, we updated the *Tiriba product line context model* with these features (see Figure 3 (right)). The addition of these features may impact on both the Tiriba application *design* and *dependability analysis*. The addition of an application-specific function, e.g., *redundant autonomous pilot*, not available in the Tiriba SPL core assets, to a system variant may also impact on design and dependability properties.

[11] Available on-line: https://github.com/aloliveira/aadl-error-annex-and-bvr

After specifying feature and context models for agriculture (**TFC-ALL**) and environment monitoring (**TFC-MAT**) applications, by choosing system and usage context features defined in the Tiriba SPL domain model, we started the product derivation process. For each TFC system variant, the following artefacts were input to the BVR toolset: the TFC-SPL *feature* and *context* models, the product feature and context models, the TFC-SPL variability model, and Tiriba Flight Controll AADL design enhanced with AADL Error Annex dependability annotations[7]. Thus, we obtained TFC-MAT and TFC-ALL variant-specific ***AADL design*** and ***error*** models. Variability management in the TFC-SPL enabled the systematic reuse of almost 80% of HARA and component fault modeling dependability information, produced during the domain engineering phase, in the derivation of each Tiriba system variant.

4.3.2 | Tiriba Product Hazard Analysis and Component Fault Modeling

By combining *rainy* and *stormy weather condition* usage context features added to the TFC-MAT system variant, newer scenarios, not predicted in the domain engineering phase, that may impact on system dependability properties can emerge. Thus, we have considered the TFC-MAT system variant operating under *rainy* and *stormy* weather conditions to perform product hazard analysis and component fault modeling. We did this to identify combinations among *component failures*, which were not earlier identified in the domain engineering phase, that may lead to the occurrence of *system* and component-level failures.

We estimated the risk for overall safety posed by each identified product-specific hazard in different scenarios, based on *severity* and *probability* risk tolerability criteria defined in SAE ARP 4754A. Tiriba product hazard analysis and component fault modeling tables are available elsewhere[46]. During TFC-MAT product hazard analysis, different hazards, with different causes and risks posed for system dependability were identified in the aforementioned scenarios.

A ***delay in receiving pilot commands*** hazard, with ***catastrophic*** *severity*, and *low* **likelihood** (i.e., ***10e-9 per hour of operation***), can emerge due the occurrence of late failures in both the ***FSC*** and ***PWM Decoder*** component's *outputs* in the **TFC-MAT** system variant operating under *stormy* weather conditions. On the other hand, when the **TFC-MAT** system variant is operating under ***rainy*** weather conditions, the occurrence of an ***early*** failure in the ***FSC.filteredControls*** output **OR** a ***commission*** failure in the ***PWMDecoder.flightControls*** output can lead to the occurrence of ***reception of pilot commands earlier than intended*** hazard, with a ***hazardous*** *severity* and *probability of occurrence* of ***10e-7 per hour of operation***. From the analysis of *risk classification* associated with TFC-MAT product-specific hazards, we assigned **DAL A** to mitigate effects of the occurrence of a ***delay in receiving pilot commands***, and **DAL B** to minimize the effects of the occurrence of ***receiving pilot commands earlier than intended***.

The emergence of two additional *hazards* in the TFC-MAT system variant operating in a controlled airspace under ***stormy*** and ***rainy*** weather conditions may impact on the structure of reused component fault models. Thus, ***additional*** component ***failure modes*** that contribute to the occurrence of product-specific hazards can be raised. Therefore, we enhanced the Tiriba **BCP component fault model**[22] with additional ***output deviations*** that may contribute to the occurrence of two additional TFC-MAT application-specific hazards identified during product hazard analysis.

TFC-MAT product-specific HARA information and component fault models can be added to the Tiriba SPL repository to be further available for reuse in the development (derivation) of other system variants from Tiriba SPL core assets. TFC-MAT product-specific ***hazards*** and ***component failure data***, identified during iterations of the *hazard analysis* and *component fault modeling* in the application engineering phase, may lead to different failure/fault propagation not predicted during the TFC-SPL dependability analysis. Thus, different fault trees, with different fault propagation, and FMEA results with different component failure effects on overall safety can be generated for a particular TFC system variant.

4.3.3 | Synthesis of Fault Trees and FMEA Results for Tiriba System Variants

Product/variant-specific TFC AADL design and error models were input to generate fault trees for 10 product-specific hazards (for four different TFC system variants), and FMEA results were synthesized from the generated fault trees. Figure 6 shows excerpts of the *No pilot commands* fault trees generated for the **TFC-MAT** and **TFC-ALL** system variants. The *No pilot commands* fault trees generated for two different system variants show the impact of SPL variation on ***hazard causes***. Thus, the occurrence of an *omission* of *PWMDecoder.flightControls* **AND** *FailSafeController.filteredControls* component's outputs leads to the occurrence of the ***absence of pilot commands*** system failure when **TFC-MAT** system variant is chosen (see Figure 6 (left)). On the other hand, the occurrence of an *omission* of *ModeSwitcher.controlMode* component output failure in **conjunction** with the two aforementioned output failures are the causes of the ***absence of pilot commands*** when **TFC-ALL** system variant is chosen (see Figure 6 (right)).

Variation in the *No pilot commands* fault tree *gates* propagates throughout the number of *failure cut sets*. A *failure cut set* is a combination of *basic events* that can cause the *top event* of a fault tree (i.e., a system-level failure)[17]. We found an example of such variation in the number of *failure cut sets* that contribute to the occurrence of an *omission of pilot commands* system failure in the Tiriba *No pilot commands* fault tree, which may change according to the chosen system variant. Thus, 60 *failure cut sets* may contribute to the occurrence of an *omission of pilot commands* when **TFC-MAT** system variant is chosen. On the other hand, 108 *failure cut sets* may contribute to the occurrence of the same *top event* from *No pilot commands* fault tree when the TFC-ALL system variant is chosen. Such a difference is justified by the increase in the number of *components* and *failure modes* that contribute to the occurrence of *No pilot commands* fault tree top event in the **TFC-ALL** system variant.

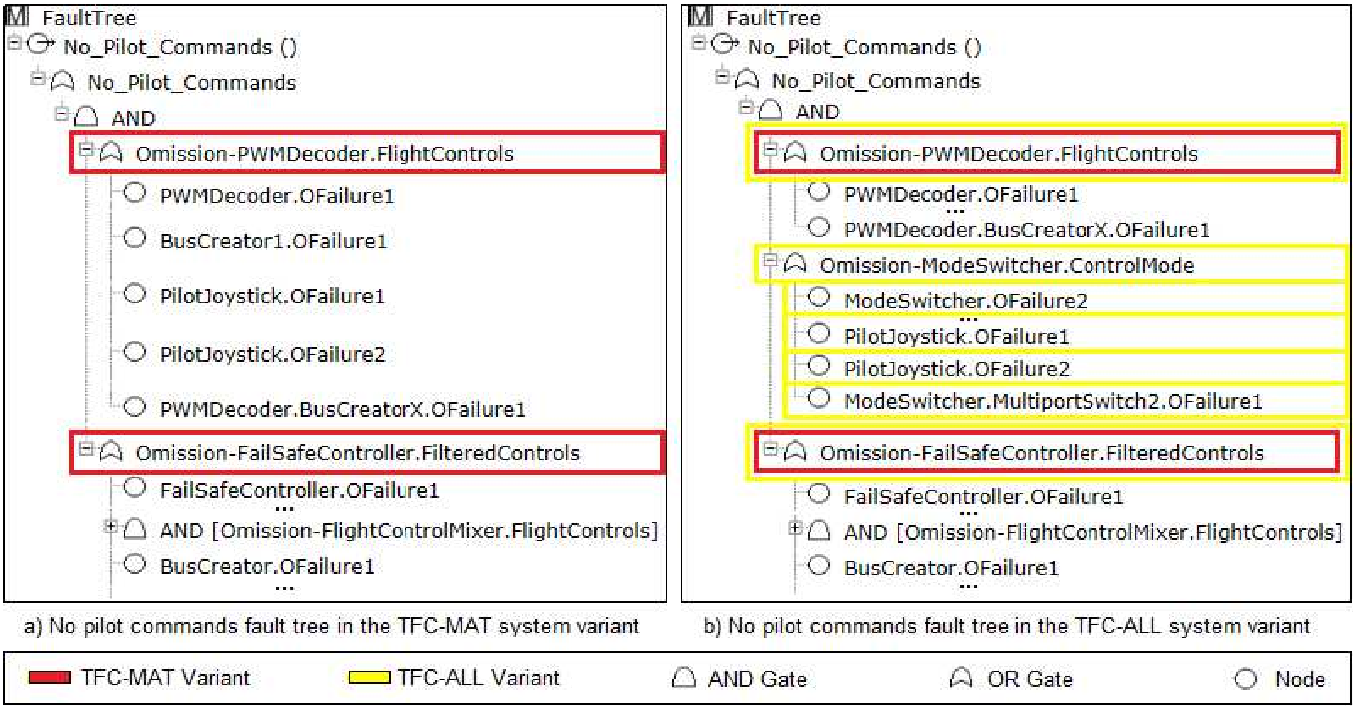

FaultTree
No_Pilot_Commands ()
No_Pilot_Commands
AND
Omission-PWMDecoder.FlightControls
PWMDecoder.OFailure1
BusCreator1.OFailure1
PilotJoystick.OFailure1
PilotJoystick.OFailure2
PWMDecoder.BusCreatorX.OFailure1
Omission-FailSafeController.FilteredControls
FailSafeController.OFailure1
...
AND [Omission-FlightControlMixer.FlightControls]
BusCreator.OFailure1
...
FaultTree
No_Pilot_Commands ()
No_Pilot_Commands
AND
Omission-PWMDecoder.FlightControls
PWMDecoder.OFailure1
...
PWMDecoder.BusCreatorX.OFailure1
Omission-ModeSwitcher.ControlMode
ModeSwitcher.OFailure2
...
PilotJoystick.OFailure1
PilotJoystick.OFailure2
ModeSwitcher.MultiportSwitch2.OFailure1
Omission-FailSafeController.FilteredControls
FailSafeController.OFailure1
...
AND [Omission-FlightControlMixer.FlightControls]
BusCreator.OFailure1
...
a) No pilot commands fault tree in the TFC-MAT system variant
b) No pilot commands fault tree in the TFC-ALL system variant
TFC-MAT Variant
TFC-ALL Variant
AND Gate
OR Gate
Node

FIGURE 6 TFC-MAT (left) and TFC-ALL (right) *No pilot commands* fault tree gates and nodes.

Variation in Tiriba product fault tree *gates*, *nodes*, and *failure cut sets* propagates to the*Failure Modes and Effects Analysis*[12] (FMEA). Thus, *failure modes* that *directly* or *indirectly* contribute to the occurrence of the *No pilot commands* hazard might change according to the targeted Tiriba system variant. In the FMEA results for Tiriba system variants[46], different ***PWM Decoder*** component ***failures*** may directly or indirectly contribute to the occurrence of Tiriba hazards (see Table 1) in each system variant.

Tiriba product FMEA results[46] show the *effects* of the occurrence of each component failure on *overall safety*, and whether a given *component failure* is a *single point of failure* or *not*, which may change from one system variant to another. Thus, when the **TFC-ALL** system variant is chosen, the occurrence of ***OFailure1*** and ***OFailure2*** omission failures ***indirectly*** contributes, in ***conjunction with*** failures from other components, to the occurrence of ***omission of pilot commands*** (i.e., ***no pilot commands***) system failure, and the occurrence of ***VFailure1*** and ***VFailure2*** value failures, in ***conjunction with*** failures from other components, ***indirectly*** contributes to the occurrence of the ***incorrect value for pilot commands*** (i.e., ***value pilot commands***) hazard. On the other hand, when **TFC-MAT** system variant is chosen, only the occurrence of ***OFailure1*** omission failure ***indirectly*** contributes, ***in conjunction with*** failures from other components, to the occurrence of ***omission of pilot commands*** system failure, and the occurrence of the ***VFailure1*** value failure, i.e., a ***single point of failure***[46], ***directly*** contributes to the occurrence of the ***incorrect value of pilot commands*** hazard. Finally, considering both Tiriba ***system variants***, *30 component failures* contribute to the occurrence of *system failures* in the **TFC-ALL** variant. Since the **TFC-MAT** system variant comprises *fewer* components in comparison with the **TFC-ALL** variant, only *24 component failures directly* or *indirectly* contribute to the occurrence of *system failures* in the **TFC-MAT** system variant.

5 | DISCUSSION

In this section, we present an analysis of the impact of variation in *system* and *usage context* features on both ***design*** and ***dependability analysis***, i.e., on ***hazard analysis*** and ***risk assessment***, ***allocation*** *and* ***decomposition*** *of* ***safety requirements***, and ***component fault modeling*** and ***propagation***. We performed such analysis, which is one of the contributions of this paper, by considering the following system architecture models enhanced with dependability information: *aircraft braking system*[47], *door controller*[48], *Tiriba UAV*[24,35], and *automotive braking system*[37] software product lines. Their architecture models were specified in AADL[7] and Simulink[44], and dependability annotations with the support of AADL Error Annex[7], and HiP-HOPS[8] compositional dependability analysis techniques.

[12] FMEA highlights the relationships between the occurrence of *component failures* and their *effects* on the *overall safety*.

5.1 | The Impact of Variability on System Design

In ***data-flow*** oriented architectural models, structural/architectural variability can be found in ***systems***, ***subsystems***, ***components***, their ***ports***, and ***connections*** expressed by ***flows*** from ***input*** to ***output*** ports and *vice-versa*, which may change according to the chosen *system* and *usage context* features. By considering the TFC-SPL [35,43] developed with ***Simulink model blocks***, the selection of the TFC-MAT system variant from the *Pilot Mode* variation point, by choosing *Manual* and *Autonomous Pilot* system features shown in Figure 3 (left), drives the selection of the *PWM Decoder* component and the *BCP* subsystem, their ***ports*** and ***connections*** (see Figure 4) during the *product derivation process*. It is important to highlight that variation in *usage context* features combined with variation in *system* features, and *isolated* variation in the *usage context* may also impact on the derivation of variant-specific *architectural* and *behavioural* models. Thus, architectural variation inherent to *system* and *usage context* variants can be further propagated to ***system behaviour***, which can be expressed in a ***finite state machine***.

In safety-critical SPLE processes, variation in system and usage context features may also impact on the system behaviour. Thus, FSM *states*, *state transitions*, and *events* that trigger *state transitions* may change according to the selection of the targeted system and usage context features. Variation in the FSM can directly impact on elements of the system architecture, changing *data port* values, along with the configuration of *components*, and their *connections*. Variability in a finite state machine can be found in the number and structure of the *state flows* associated with different product variants and their usage context.

Variation in a *state flow* can be found in its *input* and/or *output* data, *states*, and *state transitions*. A *state* may also have different *local variables* with different *values*. In addition, a FSM state may be involved in different *state transitions* according to the targeted product and usage context variants. Variation in a *state transition* can be found in its *source* and *target* states, and in the *event* that triggers the *transition*. The *execution priority order* and *outgoing events* of a *state transition* may also vary according to the targeted system and usage context variants. A state *Transition Event* may be triggered by different *mode/states* with different *guard conditions*. A *guard condition* should be satisfied for the *transition* from a *source state* to a *target state*. *Transition Events* may also have Timing Constraints. For example, a *transition event* should be dispatched after a system failure on an interval of one second or less than one second, depending on the targeted product variant.

Effects of a *state transition event* represent changes in *state variables*, which may vary according to the targeted system and context variants. Finally, variation in the *state transitions* may impact on the dispatch of different *outgoing events* affecting both the behavior and structure/architecture of a given system/product variant. Examples of *outgoing events* are changes on *states* and *state variables* from other finite state machines, and changes in structural/architectural model elements, e.g., *systems*, *subsystems*, *sub-components*, with their *connections* and *port values*. Thus, different *states* can be achieved and different *values* can be assigned to *state variables* according to the targeted system and usage context variants.

Variation in finite state machines can be found in the Tiriba optional mission-related features [35] expressed by the activation/deactivation of ***states*** and ***transitions*** from the ***Tiriba mission controller state machine*** (Figure 5) according to ***values*** assigned to ***FSM variables***. Thus, when the ***Entry Segment Simulation*** mission-related system/functional feature is chosen (see Figure 3 (left)), i.e., when all *Tiriba pilot mode system features* and the *uncontrolled* airspace *usage context* feature (see Figure 3) are chosen (TFC-ALL/Uncontrolled variant), the *SimEnable* state variable is set *true* (Figure 5 (right)), activating the transition to the *Simulating* state (see Figure 5 (left). In addition to the impact of *system* and *usage context* feature variations on ***architectural*** and ***behavioral*** models in conventional SPLs, such variation may be further propagated to ***dependability analysis*** in safety-critical SPL development processes.

5.2 | Variability and SPL Dependability Analysis

Variation in both SPL *architectural* and *behavioural* models, defined in *system* and *usage context* variants, can be further propagated to the safety life-cycle of a safety-critical SPL. This impacts on system Hazard Analysis and Risk Assessment (HARA) (i.e., *ISO 26262 Part 3-7: HARA*, and *SAE ARP 4754A Sec. 5.1: Aircraft and System Level FHA*), component fault analysis and modeling, and allocation and decomposition of safety requirements (i.e., *ISO 26262 Part 3-8: Functional-Safety Concept*, and *SAE ARP 4754A Sec. 5.2: DAL Assignment*). Variation in HARA can be further propagated to dependability engineering activities, required by safety standards/considerations [2,4] and certifying authorities, to achieve *system safety certification* and *component approval*. These include component fault analysis and modeling, Fault Tree Analysis (FTA) and FMEA, and allocation and decomposition of safety requirements.

The production of safety/dependability artefacts contributes to *increases* in the ***development costs*** of safety-critical systems. Understanding how SPL product/system and usage context variation impact on dependability analyses may help to achieve the systematic reuse of both system design and dependability artefacts, reducing the *certification costs* of individual *system variants*. Combinations among *system* and *usage context* variants may be useful to derive scenarios, which can be used to guide engineers in performing system dependability analysis/modeling in safety-critical SPL architectures. In a safety-critical SPL, different ***failure conditions*** can be raised, leading to different ***system-level failures*** (i.e., hazards), with different ***probability***, ***severity***, and ***criticality levels***. Different ***safety requirements***, in terms of ***functions*** or ***SILs***, can be allocated to avoid or minimize ***hazard*** and/or ***component failure*** effects on overall safety according to ***design choices*** and targeted ***usage contexts***. We present a detailed description of a set of identified variability types that can be found when performing dependability analysis for a safety-critical system and software product line in the following section.

Variability in Hazard Analysis and Risk Assessment:

During hazard analysis, different ***hazards*** and ***hazard causes*** can emerge according to the targeted ***product/system*** and ***usage context*** variants. Examples of such variation can be found in the *causes* of the ***No pilot commands*** and ***Value pilot commands*** *hazards* that may change according to the selection of Tiriba *system* variants (see Table 1). Variation in ***hazard definition*** and ***hazard causes***, identified during hazard analysis, can be further propagated throughout the ***risk assessment***. In the risk assessment, variation can be found in the ***values*** assigned to *reliability attributes*, e.g., SAE ARP 4754A *likelihood* and *severity*, used to classify the risk posed by each system *hazard* for overall safety (see ***Risk Assessment*** columns from Table 1). Thus, in the TFC-SPL, the *likelihood* of an omission of pilot commands is ***10e-9 per hour of operation*** with ***catastrophic*** *severity* when the **TFC-MAT** system variant operating in a **controlled** airspace is chosen. On the other hand, the addition of the ***Mode Switcher*** and ***Autopilot*** components, respectively representing ***assisted*** and ***automatic*** pilot mode features (see Figure 3 (left)), contributes to increase the *system reliability* when the **TFC-ALL** system variant operating in an **uncontrolled** airspace is chosen. This results in a reduction of the *severity* of omission of pilot commands to ***hazardous***.

Variability in the assignment of ***values*** to ***reliability attributes***, e.g., ***severity***, during *hazard classification*, may impact on the *allocation* and *decomposition* of ***functional safety requirements*** and/or ***Safety Integrity Levels*** (SILs) to avoid or minimize the effects of the occurrence of *hazards* on overall safety. Thus, different safety requirements can be allocated to mitigate hazard effects according to the targeted *system* and *usage context* variants. Still in HARA, after classifying the risk posed by the identified *hazards* and contributing *component failures*, variation can be found in the allocation of ***functional safety requirements*** and ***SILs*** to mitigate the effects of *system* or *component-level* failures on overall safety.

An example of variation in the assignment of safety integrity levels can be seen in the allocation of **DALs** with different degrees of stringency to mitigate the effects of the occurrence of the *value pilot commands* hazard identified during the Tiriba SPL *dependability analysis* (see Table 1). **DAL B** was assigned to mitigate the effects of this hazard in the **TFC-MAT** system variant operating in a **controlled** airspace. On the other hand, a less stringent **DAL C** is sufficient to mitigate the effects of this hazard in the **TFC-ALL** system variant.

Variation can also be found in functional safety requirements, expressed in terms of architectural decisions that must be taken to eliminate or minimize the effects of *system* or *component* failures, which might change according to the targeted *system* and *usage context* variants. In the Tiriba product line, the control system architecture should be ***Redundant*** when the *controlled airspace*[27] usage context is chosen[24]. On the other hand, a ***non-Redundant*** control system architecture is sufficient to ensure the safety of the Tiriba UAV operating in an *uncontrolled airspace*.

Variation and its Impact on Allocation and Decomposition of Safety Requirements:

Variability in the allocation and decomposition of SILs relates to the variation on the mitigation mechanisms for handling the risk posed by a given system *hazard*, *component failure*, or *component*, which might change according to the targeted *system* and *usage context* variants. Variation in the SILs allocated to mitigate ***hazard effects*** in different system variants may be further propagated to their *decomposition* throughout ***component failures***, identified during ***component fault modeling***, that directly or indirectly contribute to the occurrence of system hazards.

Table 2 shows an example of variation in the ***decomposition*** of ***safety requirements***, stated in terms of DALs, assigned to mitigate the effects of hazards in different variants (see Table 1) throughout the Tiriba *Barometric Processor* and *PWM Decoder* components and their failure modes. **DAL C** is sufficient to mitigate the effects of the occurrence of the ***OFailure1*** failure on the ***PWM Decoder*** subsystem in the **TFC-ALL** system variant. On the other hand, when **TFC-MAT** variant is chosen, **DAL A** should be assigned to mitigate the effects of the occurrence of this *failure mode*. Variation in the allocation fo SILs to *component failures* of a given component in the ***same*** system variant is further propagated throughout the assignment of SILs to ensure the safe use of the component in a particular system variant.

Considering **DAL A** and **DAL E**, respectively assigned to mitigate the effects of *omission* and *value* failures in the *PWM Decoder* component (column **FM-DAL:MAT** from Table 2), **DAL A** must be assigned to ensure the safe use of this component in the **TFC-MAT** variant. Additionally, we can find variation in the SILs assigned to mitigate the *failure effects* of different *components* in the *same* system variant, e.g., **DAL C** assigned to the ***Barometric Processor***, and **DAL A** to the ***PWM Decoder*** in the TFC-MAT variant (see Table 2).

Variation in the allocation of SILs to mitigate *failure modes* of a component in different system variants can be further propagated to the assignment of SILs to ensure the safety of a given SPL component in different system variants. Considering the ***PWM Decoder*** component and its *failure modes* (Table 2), **DAL C** is sufficient to mitigate component failure effects in the TFC-ALL variant, and a stringent **DAL A** is required to ensure the safe use of the ***PWM Decoder*** in the TFC-MAT variant.

Variation in the assignment of SILs to mitigate failure effects of a given component in different variants can be further propagated to the assignment of SILs to ensure the safety of an SPL component across different system variants, i.e., across the SPL. We can perform an analysis of the safety requirements that should be allocated to ensure the safe use of an SPL across a set of targeted variants on the basis of the following principle: the most stringent safety requirements, expressed in terms of SILs, assigned to a failure mode of a component across multiple system variants must be the SIL to be assigned to ensure its safe use across the SPL. From the analysis of Table 2, a stringent **DAL A**, and a less stringent **DAL C** must be respectively assigned to ensure the safe use of the *PWM Decoder* and the *Barometric Processor* components across Tiriba system variants.

Variability in the allocation and decomposition of SILs may impact on the structure and costs of both *system variants* and *software product line development processes*, since prescriptive safety standards/considerations, e.g., ISO 26262 for automotive, aerospace DO-178C and SAE ARP 4754A, establish different objectives, system engineering activities, e.g., verification, validation, and testing, to be carried out, and artefacts to be produced to achieve these objectives for each level of integrity.

Addressing more stringent SILs demands achieving the most stringent *objectives*, by performing stringent system engineering activities to produce expensive development artefacts, thus, increasing the development and certification costs. Allocating less stringent **SILs** to *less-critical* SPL components and most stringent SILs only to *highly-critical* components can reduce both system's (variant) and SPL development and certification costs. A *heuristic* that expresses the relative cost jumps of developing critical system components to address different SILs, e.g., in terms of DALs, can be used to support engineers in estimating system/SPL development costs according to the SILs allocated to system hazards and component failures.

For example, we can adopt the following *cost heuristic* to estimate the costs of developing the TFC-SPL: ***0*** to address **DAL E**, ***10*** for **DAL D**, ***20*** for **DAL C**, ***40*** for **DAL B**, and ***50*** for **DAL A**. We use this cost heuristic for illustrative purposes, but any other that engineers find more suitable can be used instead. By considering this cost heuristic, and where **DAL A** and **DAL C** are assigned to ensure the safe use of the **PWM Decoder** and the **Barometric Processor** subsystem components across the TFC-SPL (see column **DAL-SPL** from Table 2), the estimated cost for developing these TFC-SPL components is 70 (20 (DAL C) + 50 (DAL A)), instead of 100 in case of assignment of **DAL A** to both components. Thus, instead of allocating the most stringent DAL A assigned to a component failure to ensure the dependability of all components in a given system variant or across the SPL, the decomposition of safety requirements may support engineers on structuring cost-effective Tiriba system and software product line development processes.

The SIL decomposition process allows engineers to assign *objectives* to a given *component* or a *subset of components* according to their *level of integrity*, instead of allocating highly stringent objectives to all subsystems/components of a system variant. Thus, the assignment of less stringent safety objectives to less critical components means less effort and costs need be considered for developing system components, addressing the safety requirements without incurring unnecessary costs and without compromising safety.

By analyzing the DALs allocated to mitigate the failure effects of components in the TFC-MAT system variant (see Table 2), we noted that the *PWM Decoder* is a highly critical component with **DAL A**. Thus, expensive objectives with *independence*, e.g., *SAE ARP 4754A - aircraft functional hazard assessment*, and *DO-178C - verification of additional code*, should be addressed. Less critical components, e.g., the *Barometric Processor* **DAL C** subsystem, demand less stringent objectives that *do not* require independence[4] (see Table 2). Thus, the definition of development processes according to the level of integrity of each system component contributes to avoiding unnecessary costs for achieving compliance with standards without compromising safety.

Finally, it is important to highlight that when developing reusable system/software components, all variability aspects of each component should be considered from the initial stages of the SPL life-cycle, and the most stringent SIL assigned to a given component in different usage contexts should be assigned/allocated to that component to ensure its safe use across the SPL, i.e., across a range of system variants/configurations. Thus, product/system and contextual variability will not change the mitigation mechanisms for components in specific system variants.

Component Fault Modeling and Propagation & Product Line Variation:

In the safety engineering life-cycle, *component fault analysis and modeling* is intended to: ***identify*** how *software* components contribute to the occurrence of potential *system-level* failures identified during ***hazard analysis***, and estimating the reliability, e.g., in terms of ***failure*** and ***repair*** rates, of **hardware** components. Variation in the system ***hazards*** and their ***causes*** can be further propagated to how components contribute to the occurrence of *system hazards*.

Variability in *component fault modeling* can be found in component *output deviations* that may contribute, in some way, to the occurrence of **system-level failures**, which might change from one targeted *system* and *usage context* variant to another (see column *Output Deviation* from Table 3). Such variation can be further propagated to the ***causes*** of ***deviations*** in ***component outputs***, which may change according the chosen system variant and usage context. Thus, different ***deviations*** in *component inputs*, ***component internal failures***, or *combinations* of component ***input deviations*** and **internal failure modes** specified in a *failure expression*, which contribute to the occurrence of a given *output deviation*, may also be raised according to the targeted *system* and *usage context* variants (see column *Failure Expression* from Table 3).

Variation in the product line design (see *subsection* 5.1), i.e., in *architectural* and *behavioral modeling*, may also impact on how component *failures* or *faults propagate* to other *components. Output deviations* of a given component may be propagated to different *components* according to the chosen *system* and *usage context* variants. In addition, variation in the *design* and *usage context* may also impact on different *input deviations* and *internal failures* that may contribute to the occurrence of the *output deviations* of a component, changing the way *failures propagate* inside the component (i.e., ***internal fault propagation***).

Different system and usage context variants may lead to different *connections* among components, via component *ports*, which may change the way in which *failures propagate* both ***inside*** the component, and throughout the ***system architecture***, i.e., ***external fault propagation*** (see Component Failure Data columns from Table 3). It is important to highlight that variation in the *causes* of *output deviations* (see column Failure Expression from

Table 3) may impact on both *internal* and *external* failure propagation of the component, thus, changing how *input* and *internal* failures propagate *inside the component*, and how component *output failures* are propagated to *other components* of the system architecture. Finally, we can also find variability in the assignment of *values* for *reliability attributes*, e.g., *failure and repair rates*, to a given hardware component, which may change according to the targeted system variant.

Variability in *hazard analysis* and *component fault modeling* propagates to fault tree *gates* and *nodes*, and *failure cut sets* in **FTA** (see Figure 6), and in the way that components contribute, i.e., with *direct* or *indirect* failure modes, to the occurrence of the *hazards* in different system variants in **FMEA** (see subsection 4.3.3). The analysis of FTAs and *FMEA results* for different system variants (see sub-section 4.3.3) provides the evidence of *traceability* of variation in the design and usage context throughout the *cause-effect* relationships between *component-level* failures and *system-level* failures. Such analysis provides insights into how SPL components can fail, and contribute to the occurrence of hazards across different system variants, providing feedback for product line engineers addressing dependability, in terms of the safety and reliability, of the components across the SPL, i.e., across a range of system variants.

Finally, variation in hazard analysis, safety requirements, component fault modeling, FTA and FMEA further propagate to the structure of product assurance cases. We can automatically generate *Assurance Cases*, with the support of model-based techniques[49], for an specific system variant from design and dependability assets. An *Assurance Case* is a *defensible*, *comprehensive*, and *justifiable argument* supported by a body *evidence* which demonstrate that the *system* is acceptably safe to operate in a particular context[50]. Automotive[2] and aerospace[4] standards and considerations, and regulations recommend the production of an *Assurance Case* for certification of critical systems. The automatic generation, and the analysis of the impact of variability on the structure of product assurance cases are outside the scope of this paper.

6 | RELATED WORK

Research on variability management with dependability artefacts is split into extensions of traditional *safety and dependability analysis* techniques, e.g., *Fault Tree Analysis* and *Failure Modes and Effects Analysis*, to suit *Software Product Line Engineering* processes[13,14,16], and model-based techniques[10,11,51,52] to support dependability analysis integrated with the system design. The most notable work in the first category is the *extension* of *Software Fault Tree Analysis* (SFTA), named *Product Line SFTA*[13,14], to address the impact of *SPL variation* on system *dependability analysis*. In the Product Line SFTA approach, each *leaf node* of a *software fault tree* is labeled with *commonality* or *variability* associated with that *leaf node*. The *Product Line SFTA* approach is built upon a technique for *developing* a product line SFTA in the domain engineering phase, and a *pruning* technique for *reusing* the SFTA in the application engineering phase.

The *Product Line SFTA* approach is further extended to *integrate SFTA results* with *state-based models*[16]. This extension allows the *mapping* of software fault tree *leaf nodes* into *components*, and modeling the *behaviour* of each component in a *state chart*. The Product Line *SFTA* and its *state-based modeling* extension considers *Fault Tree Analysis* as a *reusable asset*. However, *fault trees* can be automatically *generated* from dependability information produced during *hazard analysis* and *component fault modeling* in the domain engineering phase. Thus, *earlier variability management* of *dependability* properties on FTA and FMEA synthesis, as we presented in this paper, enables the *systematic reuse* of dependability information, and *traceability* of dependable-related variation throughout the *SPL safety life-cycle*. *Fault trees* and *FMEA* artefacts can be automatically *generated* for a particular system variant, with the support of compositional dependability analysis techniques[7,8,9], from the *reused* dependability information produced in the DEPendable-SPLE application engineering phase.

In the second category, Schulze *et al.*[11] have proposed an approach that integrates commercial *Medini* ISO 26262 compliant safety analysis and *pure::variants* tools, to enable support for variability management in functional safety-related assets, evaluated in an *automotive* case study. The Schulze *et al.* approach[11] is based on a *referencing model*, which maps *problem-domain* features with artefacts in the *solution space*, in this case, *requirements*, *fault trees*, and *safety goals*. The Schulze *et al.* approach was further extended with a process to support model-based change impact analysis of variability in automotive functional safety[51]. This process combines *variability management* techniques with *safety engineering* and *software configuration management* activities to achieve a complete safety assessment. The proposed process supports change impact analysis in the following scenarios: *(i)* when a specific variant shows undesired behaviour and it needs to be fixed, *(ii)* in cases where an innovative function requires an extension of an existing system function, and *(iii)* when the function behaviour is changed and it should be analyzed, or when a newer optional function is developed.

Similar to the Schulze *et al.* approach and its extension, the approach proposed by the authors in this paper is built upon an SPL *variability model*, linking problem-domain context and system features with artefacts from the solution space, e.g., components and their failure data. Although the Schulze *et al.*[11] approach provides support for variability management in functional safety assets, they didn't emphasize the management of the impact of *contextual* variation on *architectural* and *behavioural* models, *HARA* and *component fault modeling*, as we presented in this paper. In addition, the author's approach is applicable to domains other than *automotive*, e.g., *aerospace*, and it is independent, from underlying dependability analysis and variability management tooling support. Nevertheless, the Schulze *et al.* approach[11] and its extension[51] also provides a *good* and *efficient* solution for *variability* and *change* management on *functional safety*.

Kaβmeyer *et al.*[52] proposed a systematic model-based approach integrated with a change impact analysis approach[51]. The Kaβmeyer *et al.* tool-supported approach combines requirements engineering and architectural design, safety analysis, and variability management tools, allowing seamless safety engineering across product variants by representing safety artefacts in a homogeneous *UML-compliant* modeling notation. In their approach, HARA and component fault modeling is performed by annotating the UML model in the same way as in the DEPendable-SPLE approach.

As part of Kaβmeyer *et al.* approach[52], Domis *et al.*[10] have extended the *Component Integrated Component Fault Trees* (C2FT) technique with *variation points* and integrated it with **UML** via a profile in the Enterprise Architect tool. Although the Kaβmeyer *et al.* approach[52] and its extension[10] also provides a good solution for variability management in functional safety, they are dependent upon specific commercial tools. On the other hand, DEPendable-SPLE approach can be applied independently from underlying variability management and dependability analysis tooling support, i.e., engineers can apply the approach steps in their projects with the support of different compositional modeling and variant management techniques, e.g., Simulink/HiP-HOPS and pure::variants[11], other than those used by the authors in the case study.

7 | CONCLUSION

In this paper we presented the DEPendable-SPLE approach that extends conventional SPLE processes with support for variability management in both *design* and *dependability analysis*. The DEPendable-SPLE approach enables the *systematic reuse* of both SPL *archictural*, *behavioural*, and *dependability* models in the application engineering phase. DEPendable-SPLE is also applicable independently from underlying variability management and dependability analysis techniques and tools. In this paper, we performed DEPendable-SPLE approach steps with the support of OSATE AADL & Error Annex system modeling and compositional dependability analysis toolset, BVR variabiity mangement toolset, and OSATE AADL adapter for BVR toolset developed by the authors.

The AADL adapter to the BVR tool was developed to enable BVR to communicate with OSATE model editors for managing variability in AADL design and dependability/error models. We used these tools to support both dependability analysis and variability management steps in the Tiriba flight control SPL. DEPendable-SPLE supports the analysis of the impact of *design* and *usage context* variations on dependability analysis artefacts. Thus, we linked the Tiriba Flight Control SPL system and usage context variants to their realization in both architecture, behavioral, and dependability models. Further, we generated, with the support of the BVR toolset, multiple variant-specific design and dependability models, during the product derivation process. Thus, we achieved the *systematic reuse* of architectural, behavioural, and dependability models early in the SPL safety process.

DEPendable-SPLE enabled the *systematic reuse* of almost 80% of TFC dependability information, produced in the domain engineering phase, in the derivation of each one of the four TFC system variants. This reduces the effort and *costs* for performing dependability analysis activities for a specific system variant. With the support of compositional techniques, in this case, OSATE AADL Error Annex[7], fault trees and FMEA were generated from the reused AADL design and AADL Error Annex dependability/error models. We also presented a detailed analysis of the impact of *design* and *usage context* variations on both *design* and *dependability analysis* (i.e., hazard analysis and safety requirements, and component fault propagation). Such analysis enables the systematic reuse of dependability assets produced during the domain engineering phase. Additionally, we presented a preliminary analysis of the impact of *variation* on *allocation* of *safety requirements*, expressed in terms of *safety integrity levels*, and their *decomposition* throughout *components* and their failure modes that may support engineers on structuring *cost-effective* development processes for both SPL and/or specific system variants.

In further work on this topic we intend to focus on detailing how variability in AADL *design* and *error* models is specified and managed, and performing a user study of the BVR tool and AADL adapter developed by the authors and a comparison with existing variant management techniques. We also intend to perform a deeper investigation about the impact of design and usage context variations on SIL decomposition and development processes, and time-dependent, failure and repair behaviours of re-configurable critical systems and software product lines. We intend to investigate the implications of SPL and system version/configuration variability on both *safety* and *security* analysis. Finally, we intend to investigate the use of model-driven techniques to generate variant-specific assurance cases, and the potential of SIL decomposition techniques in supporting engineers to take architectural decisions in the design of re-configurable systems and safety-critical SPLs.

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